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Title: Deliberate exotic magnetism via frustration and topology

Author(s): Nisoli, Cristiano

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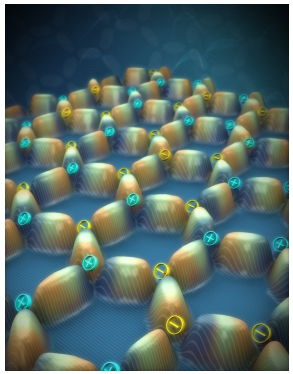
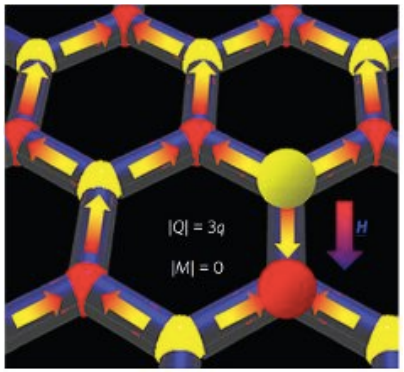
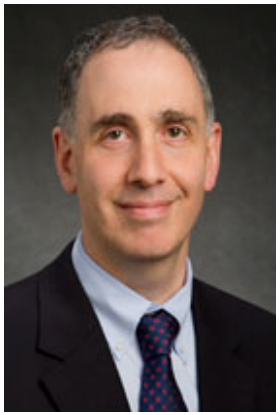
Deliberate Exotic Magnetism via Frustration and Topology





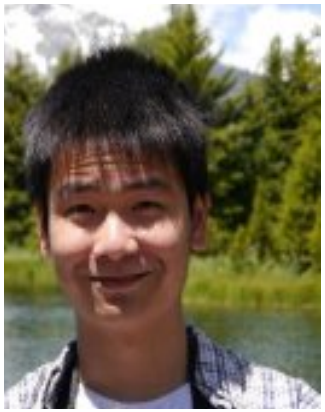
Cristiano Nisoli
Los Alamos National Laboratory

Collaborators



Peter Schiffer
UI Urbana

Ian Gilbert
NIST



Yuyang Lao
UI Urbana

Sheng Zhang
Argonne

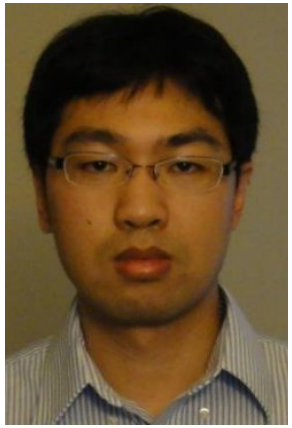
Vincent Crespi
Penn State

Gia-Wei Chern
Virginia

Muir Morrison
Caltech

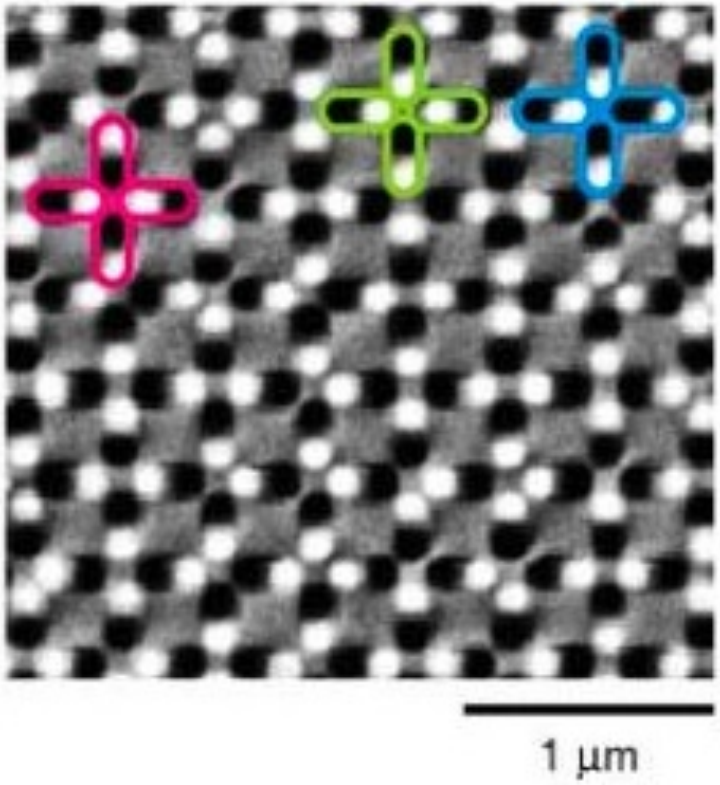
Tammie Nelson
LANL

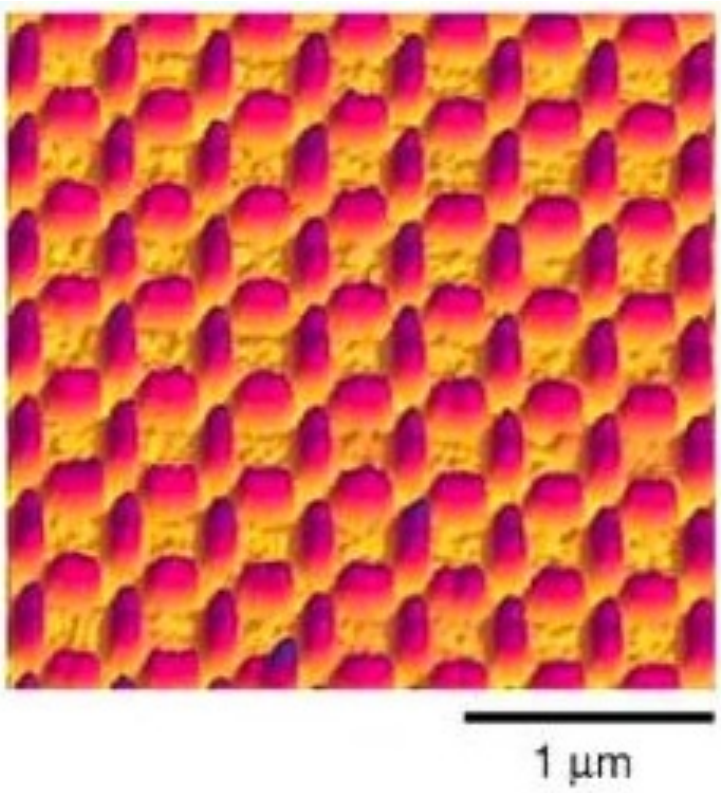
Paul Lammert
Penn State



Yifei Shi
Virginia

Artificial Spin Ice: Interacting Magnetic Nanoislands

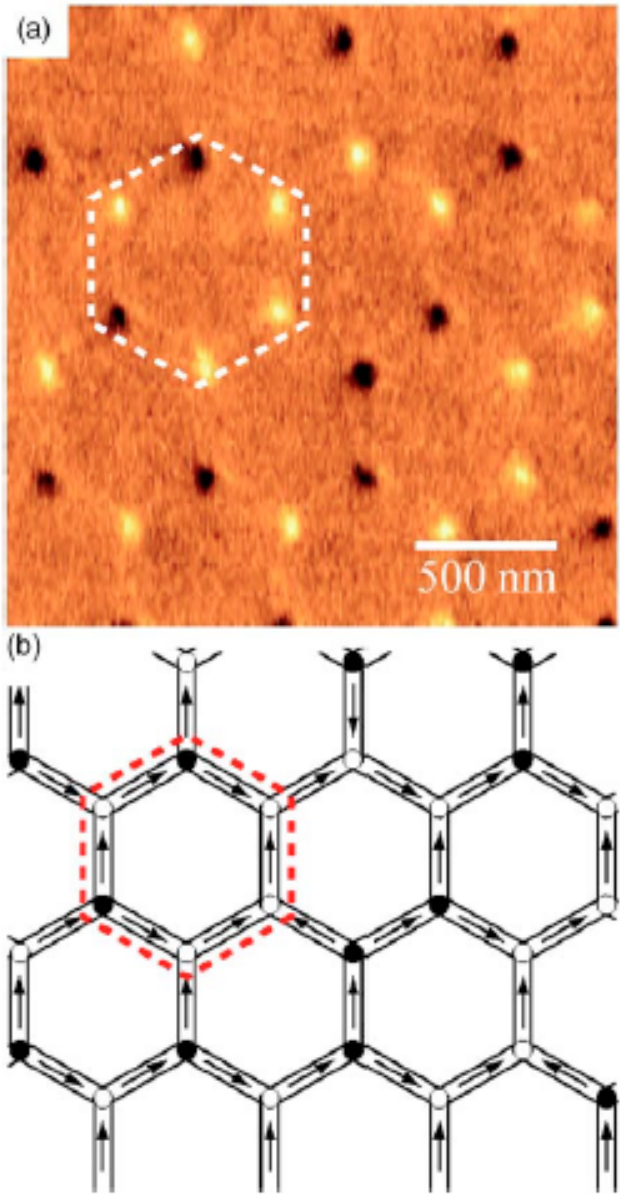




- Direct Imaging of magnetic degrees of freedom
- Designing the low energy dynamics for the collective behavior of interacting nanostructures

Nature Physics 13 (3), 200-203 (2017), Physics Today 69 (7), 54-59 (2016) , Reviews of Modern Physics 85 (4), 1473 (2013)

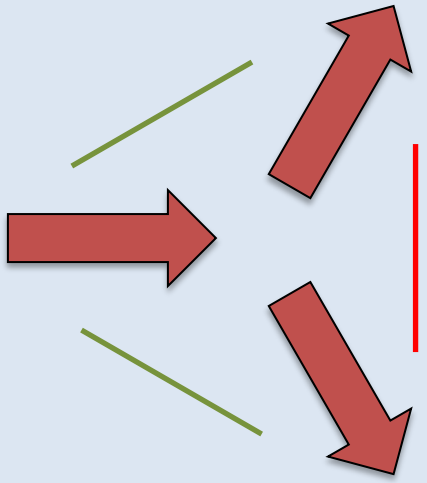
ASI Developing into a multidisciplinary field



- Hexagonal Geometry: extensive degeneracy

  Phys. Rev. B 73, 052411, 2006

  Phys. Rev. B 77, 094418, 2008



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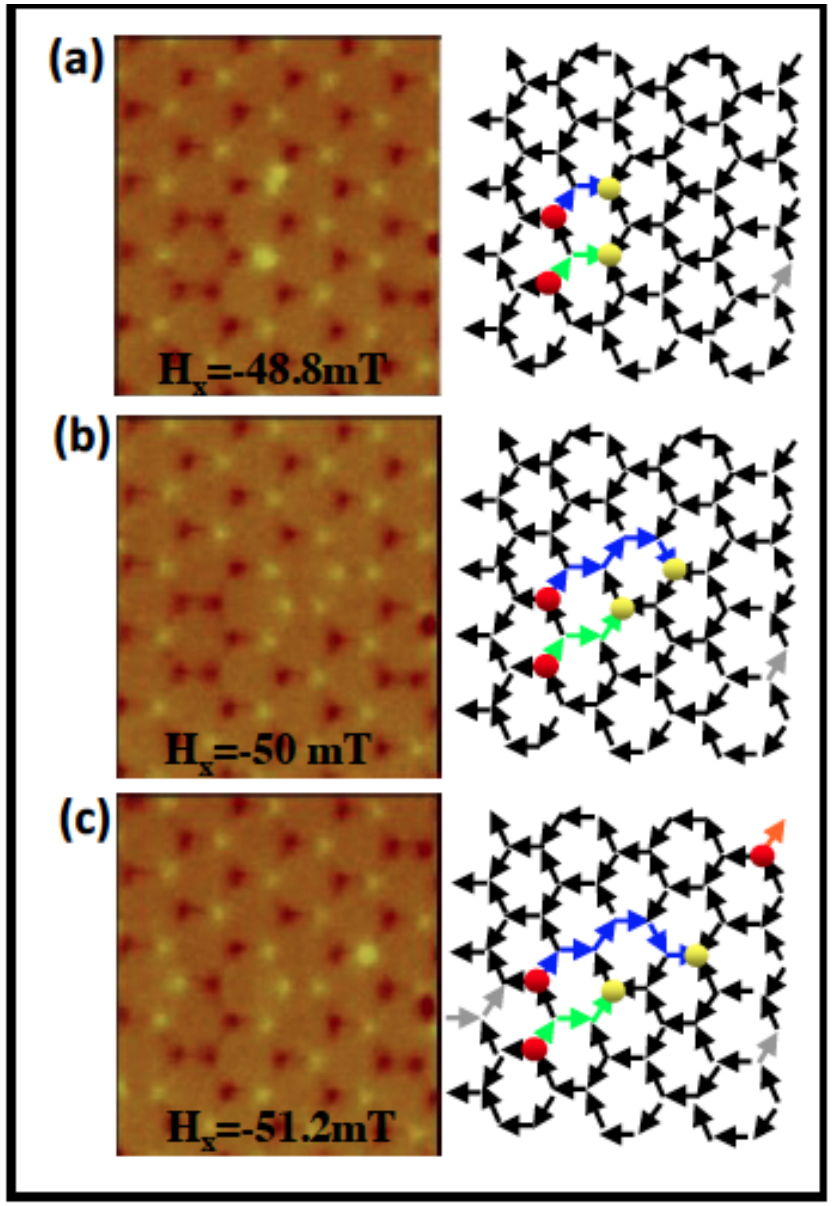

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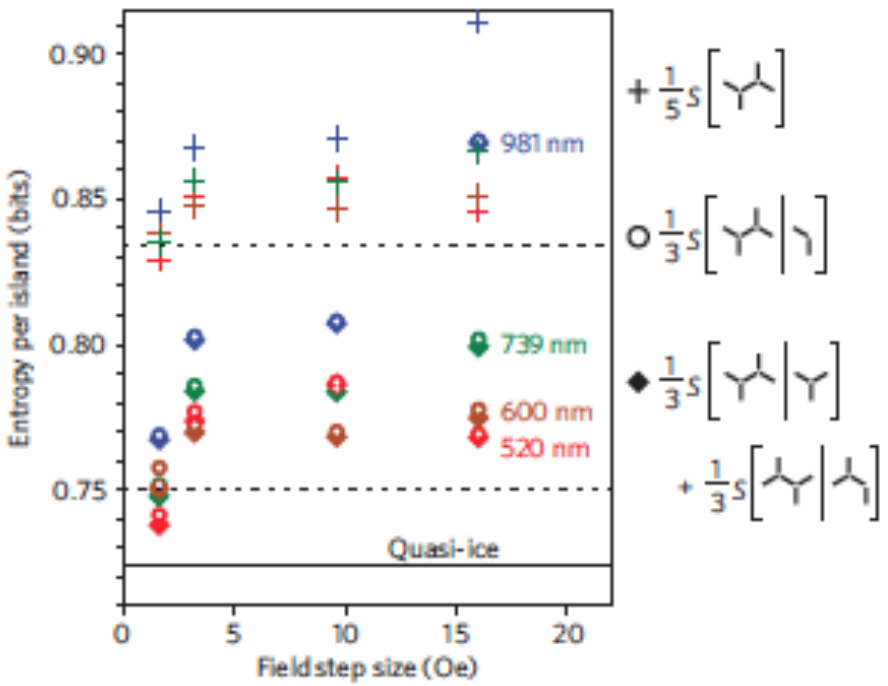

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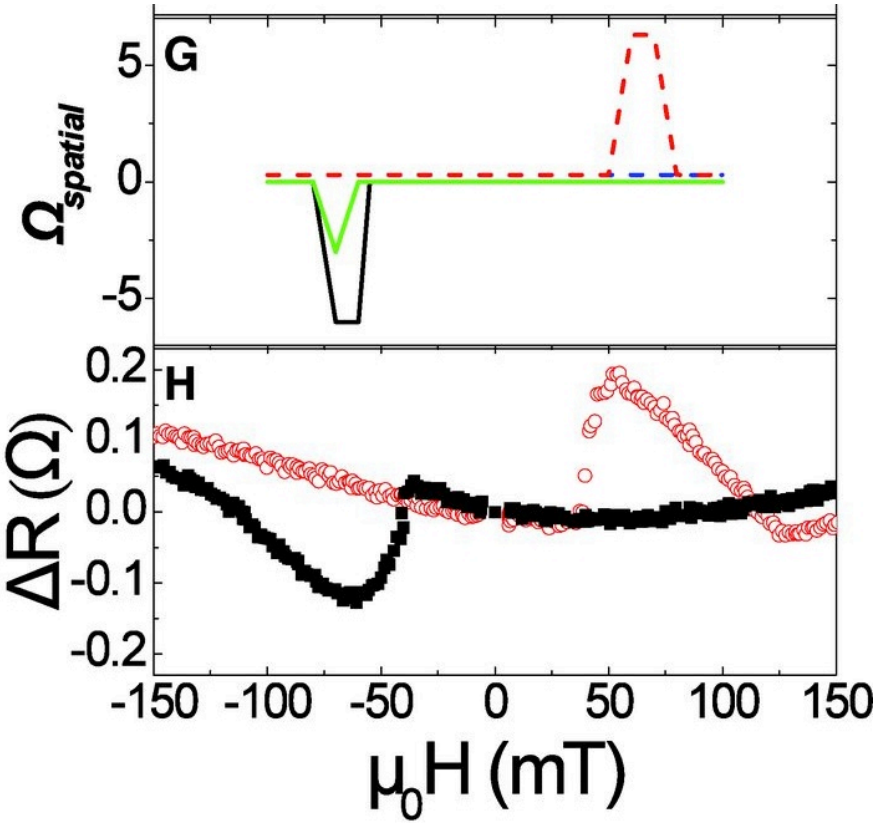
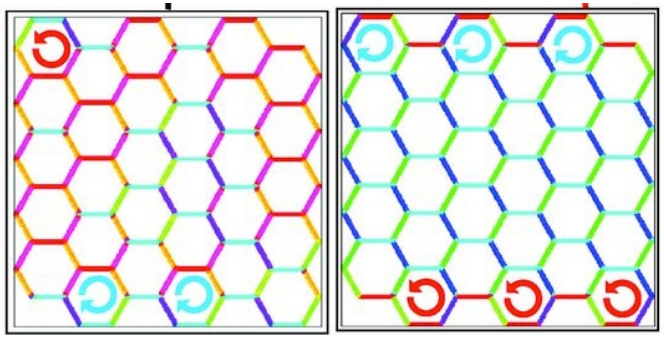
- Direct Extraction of Entropy/Shannon Information theory
  Nature Physics 6, 786, 2010

ASI Developing into a multidisciplinary field





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  Phys. Rev. B 77, 094418, 2008
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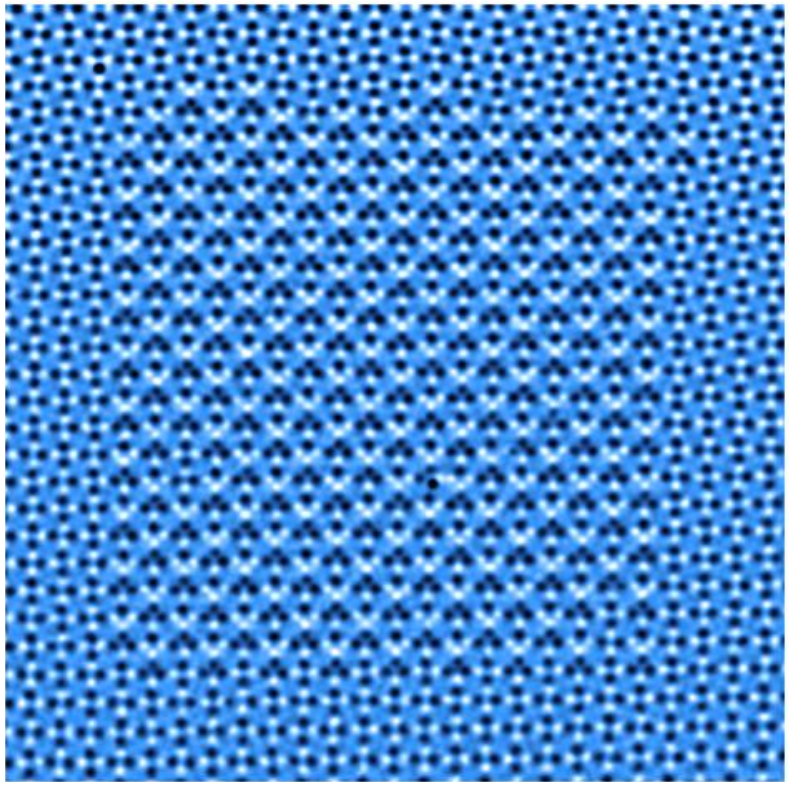
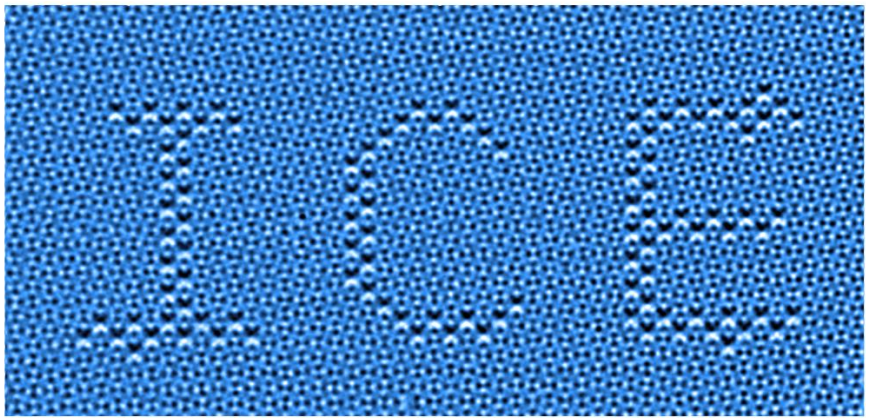
  Nature Physics 6, 359, 2010
  Nature Physics 7, 68, 2011
- Direct Extraction of Entropy, Shannon Information theory
  Nature Physics 6, 786, 2010
- Topological Hall Effect, Transport
  Science 335, 1597, 2012

ASI Developing into a multidisciplinary field





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  Nature Physics 6, 786, 2010
- Topological Hall Effect, Transport
  Science 335, 1597, 2012
- Rewritable Artificial Magnetic Charge Ice
  Science 352.6288 (2016)

Frustration

Frustration:
a set of constraints not all of which can be satisfied at the same time

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Compromises:
Attempt to optimize gains vs. sacrifices

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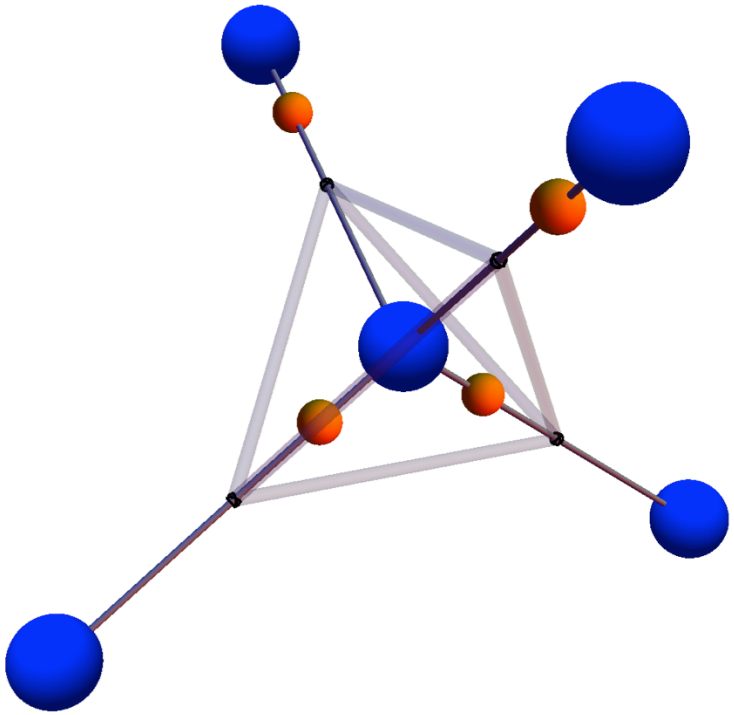
Compromises:
Attempt to optimize gains vs. sacrifices

Manifold of Choices
Something between order and disorder

Ice Rule in Water Ice and Spin Ice



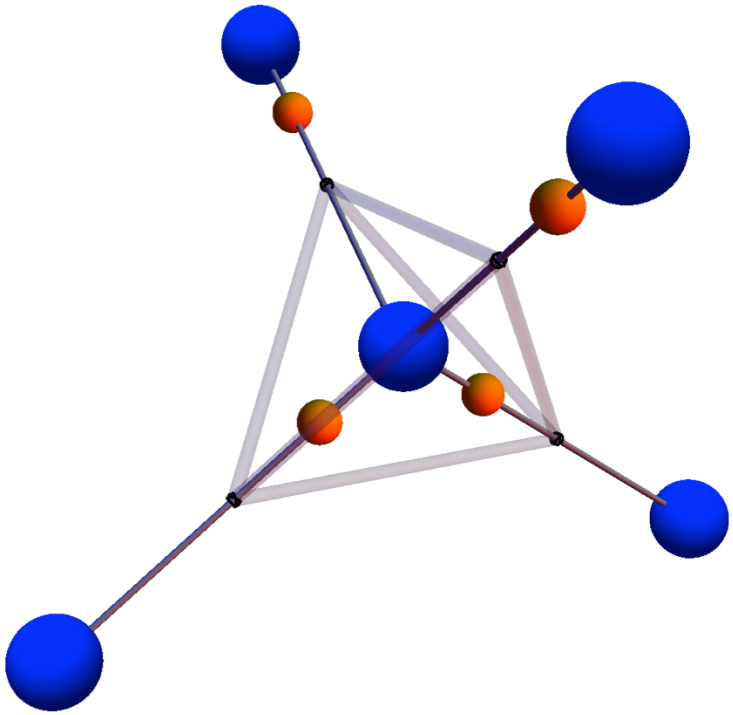
$$\Delta S = \int_{T_1}^{T_2} \frac{C(T)}{T} \mathrm{d}T$$

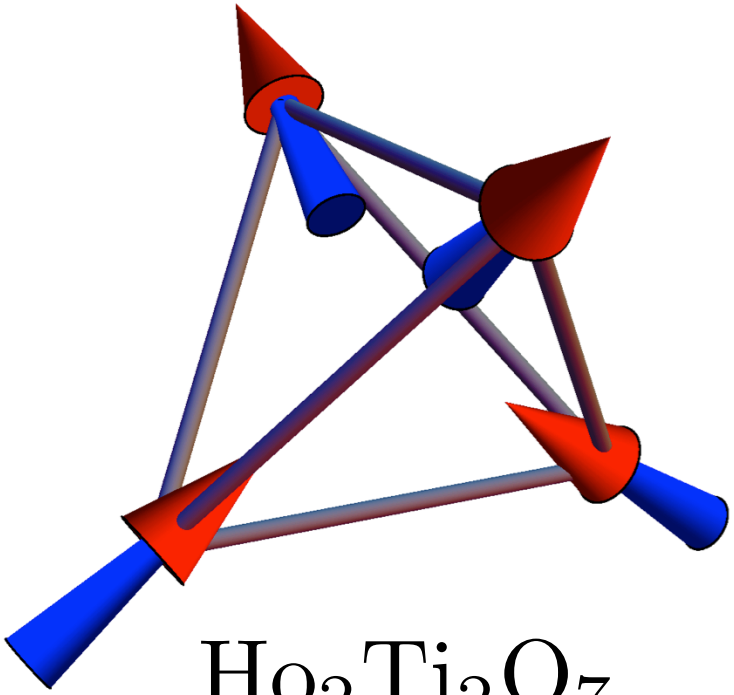
$$D = \left(\frac{3}{2}\right)^{N/2}$$

W. F. Giaque, M. F. Ashley Phys. Rev. **43** 81(1933).

L. C. Pauling, J. Am. Chem. Soc. **57** 2680 (1935).

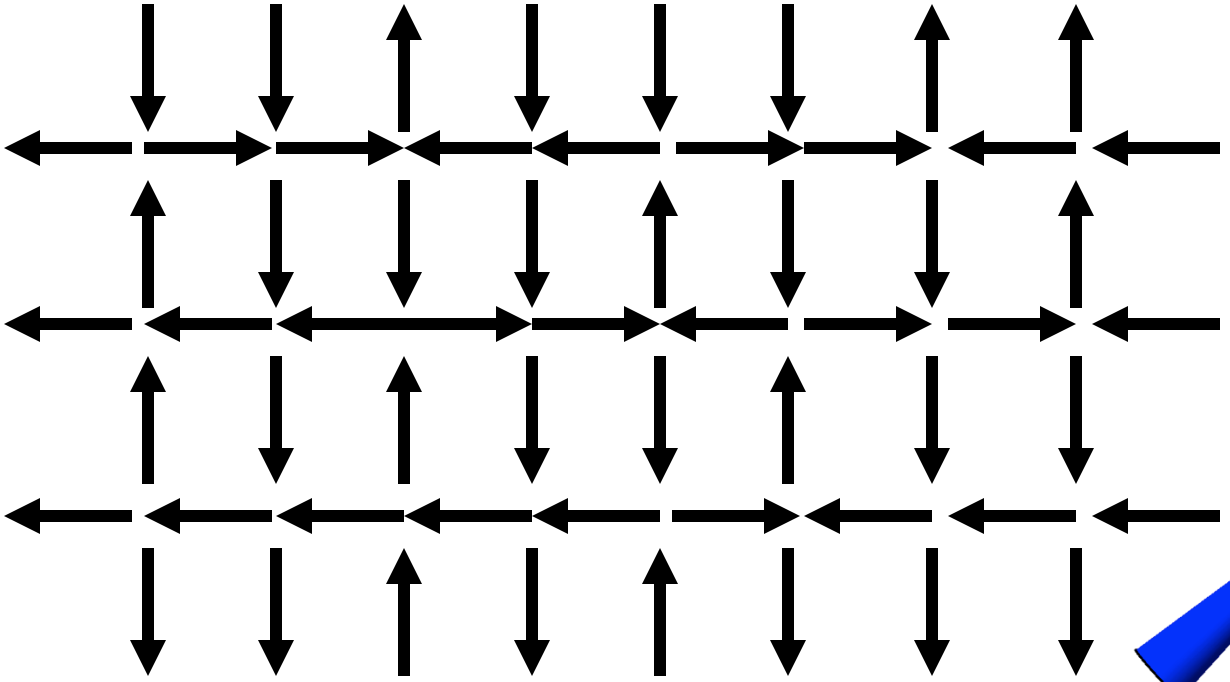
Ice Rule in Water Ice and Spin Ice

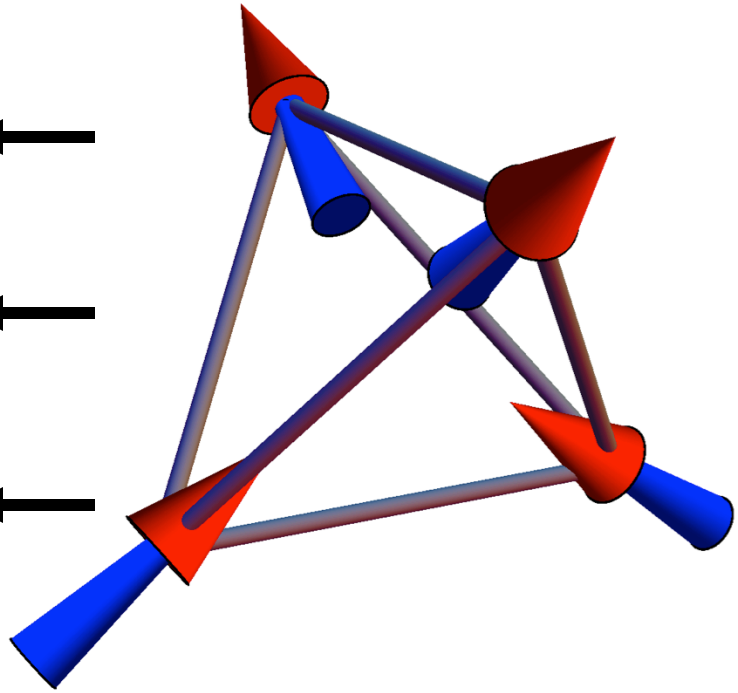




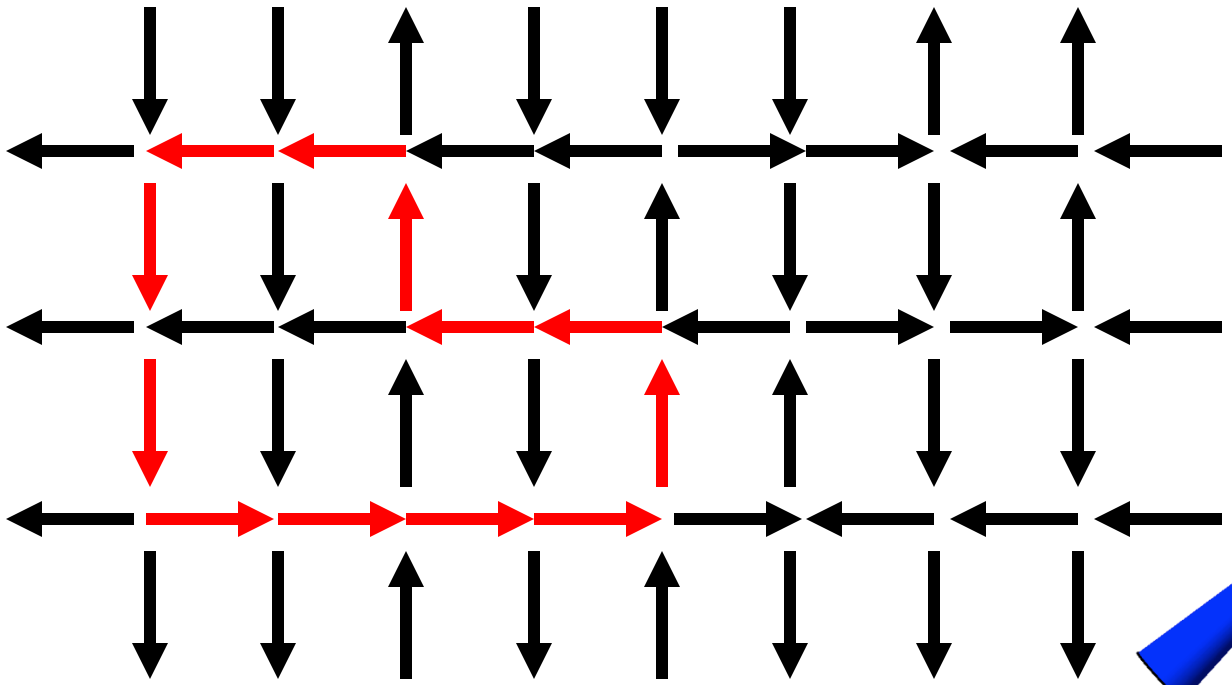
$Ho_2Ti_2O_7$

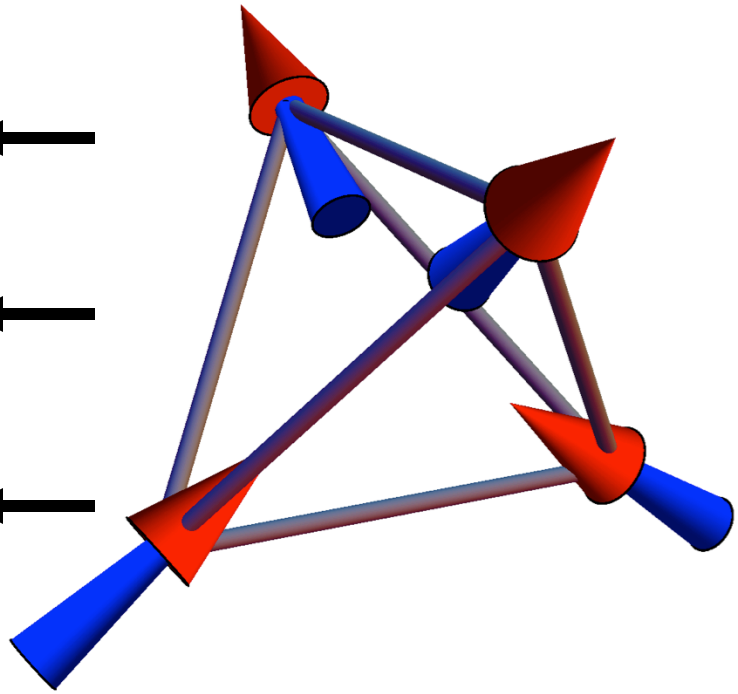
Ice Rule in Water Ice and Spin Ice



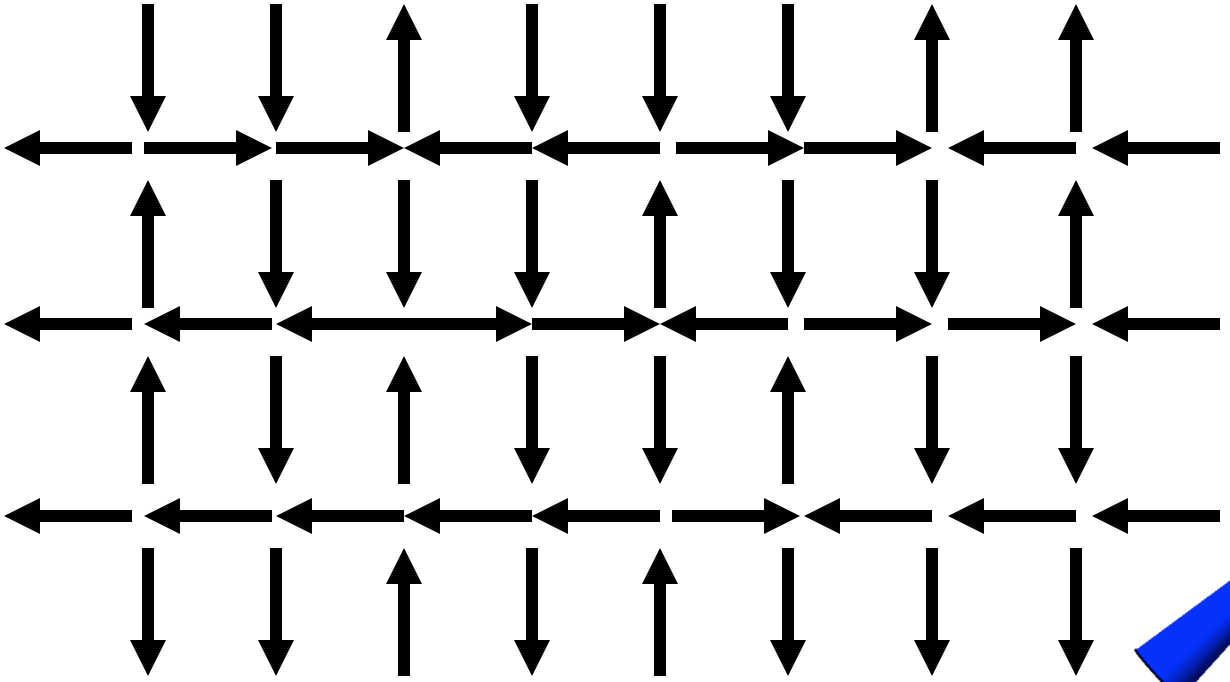


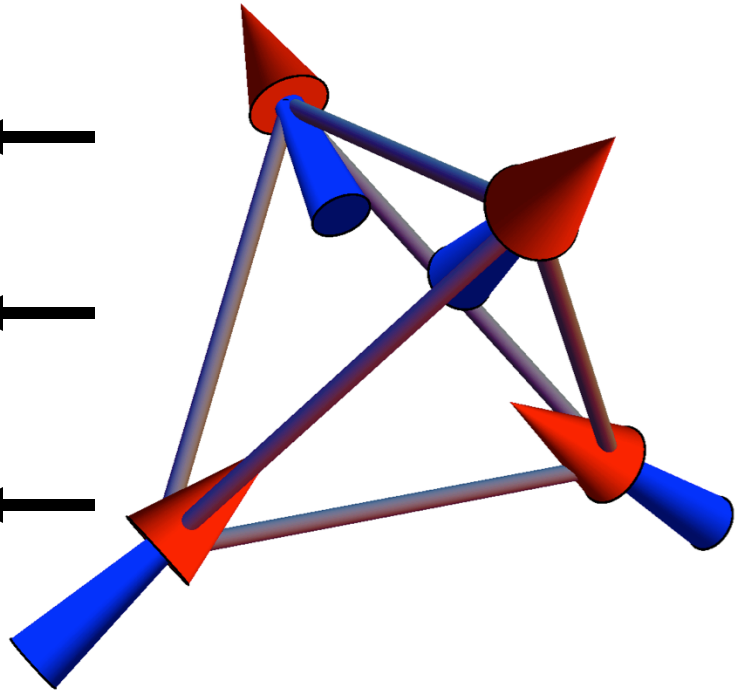
Ice Rule in Water Ice and Spin Ice



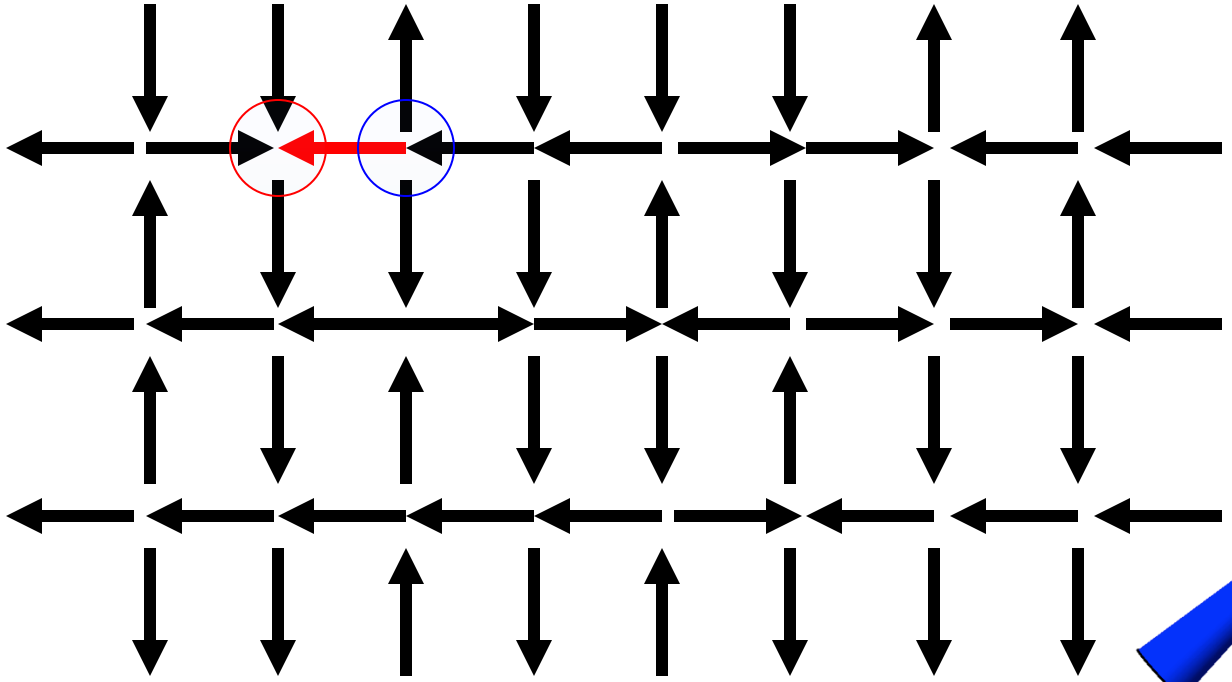


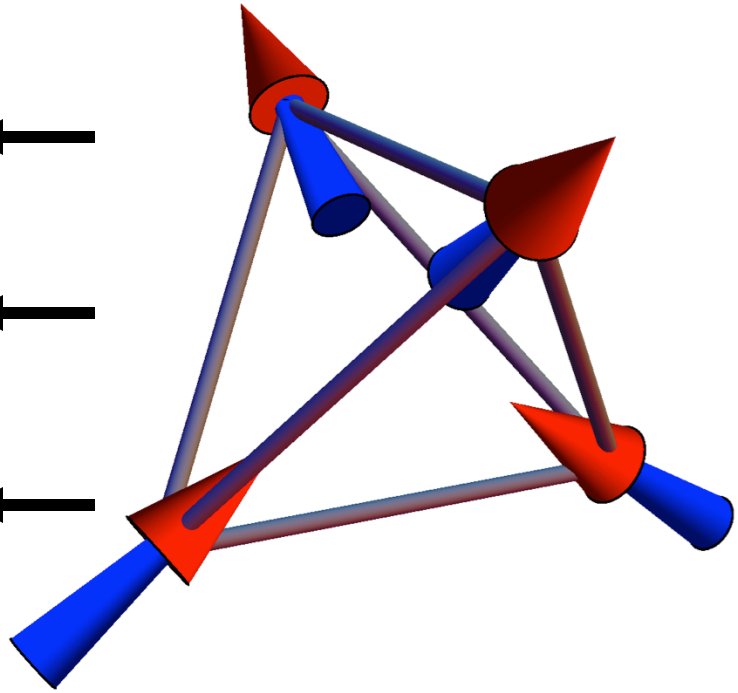
Ice Rule in Water Ice and Spin Ice



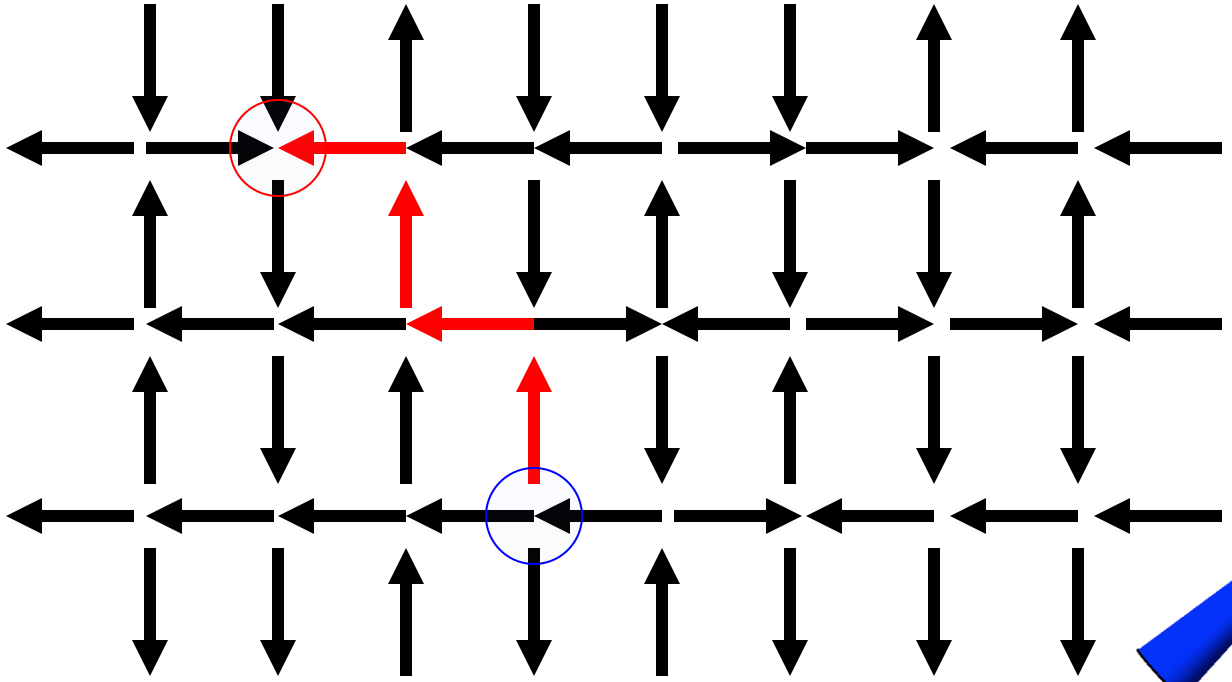


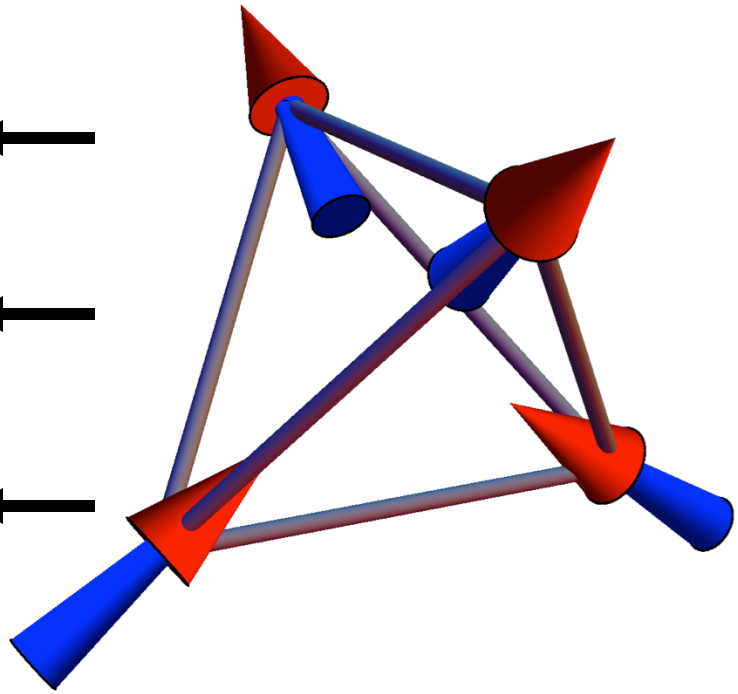
Monopoles





Monopoles





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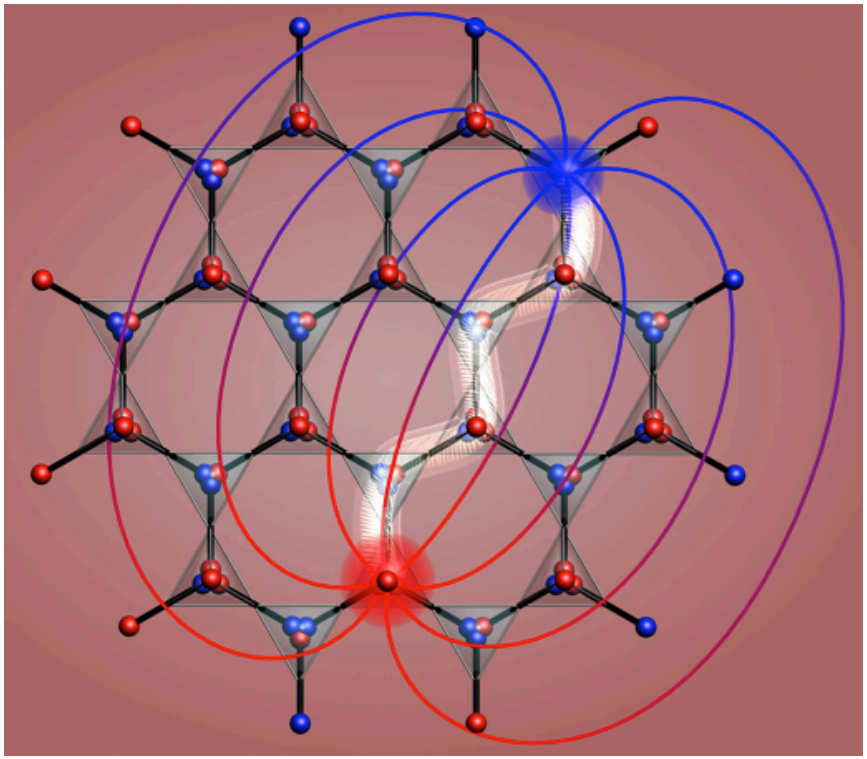
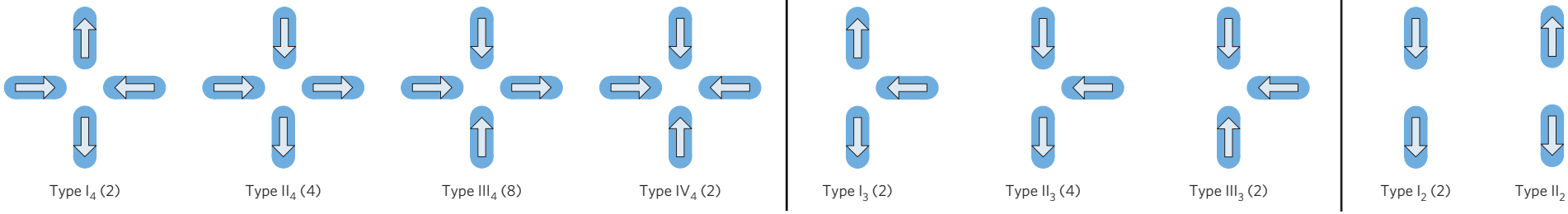
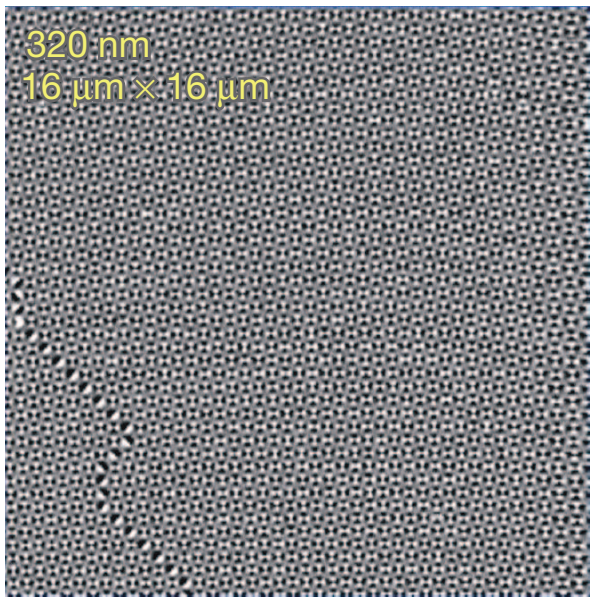


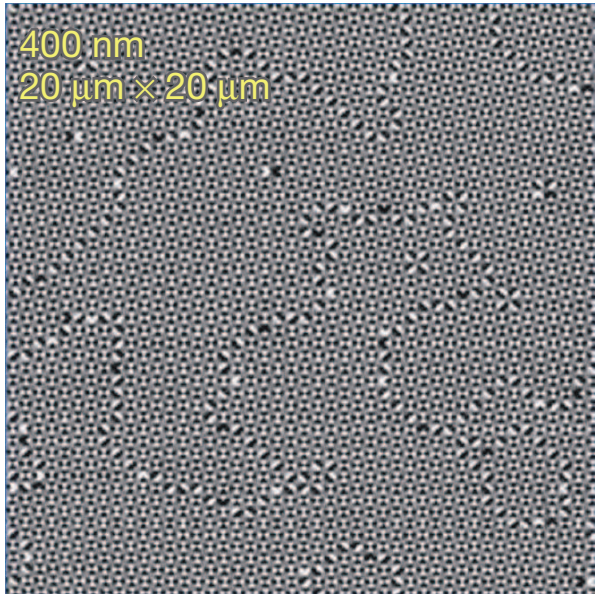
C. Castelnovo et al.
"Magnetic monopoles in spin ice."
Nature 451.7174 (2008): 42-45.

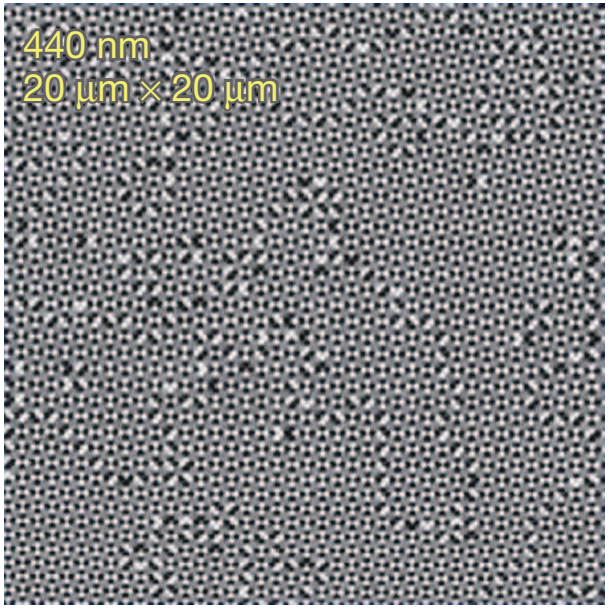
S. Bramwell at al.
“Measurement of the charge and current of magnetic monopoles in spin ice." Nature 461.7266 (2009): 956-959.

Damn! Order!



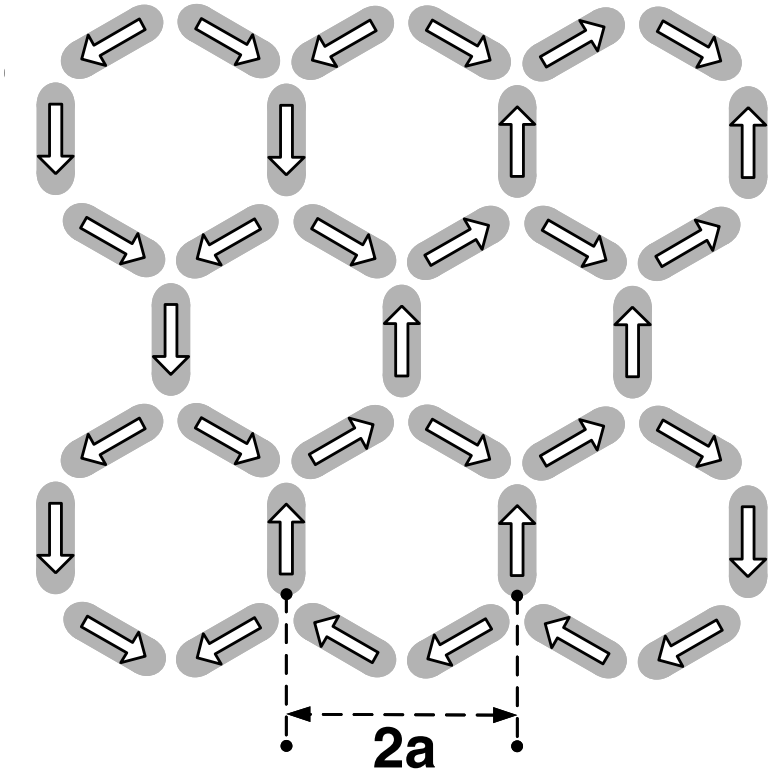


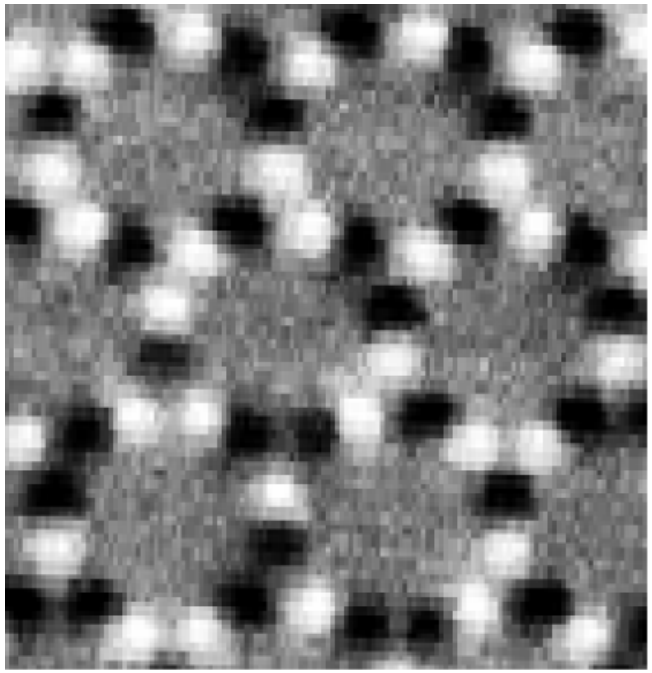




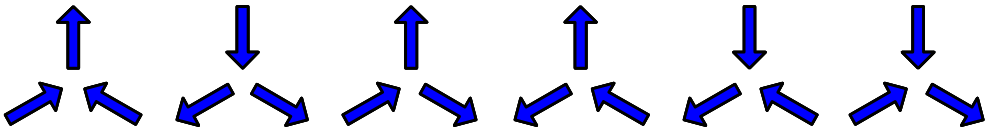
Nature 500, 553–557 2013

Kagome Ice

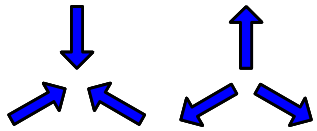




1 μm

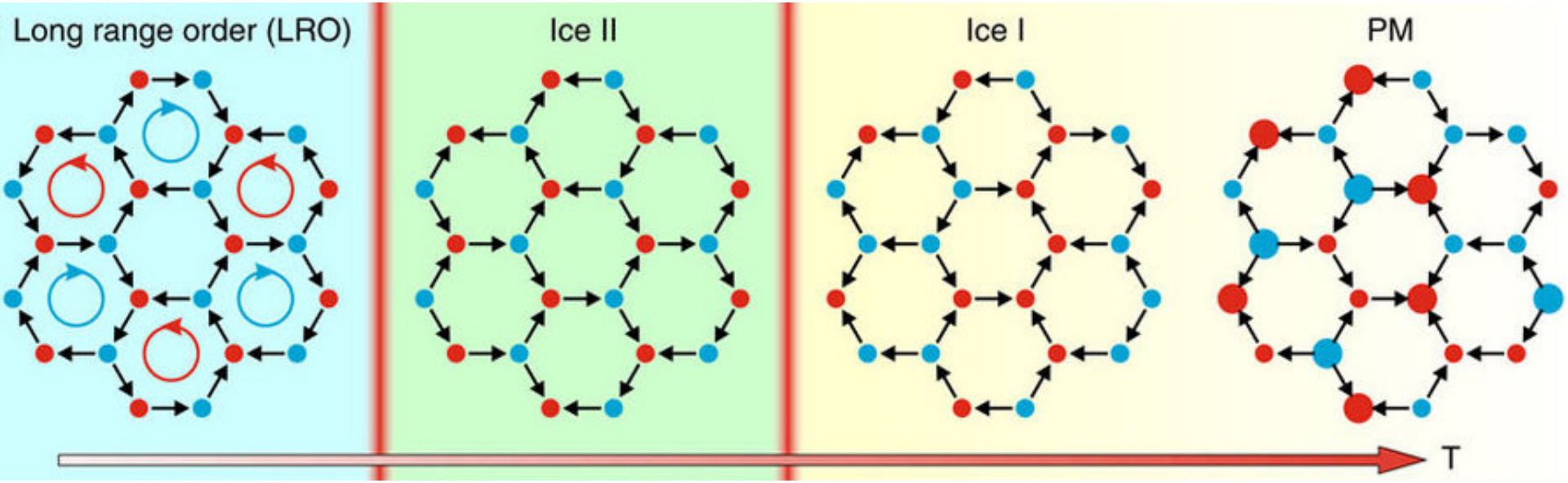


Type I
(75%)



Type II
(25%)

Kagome Ice



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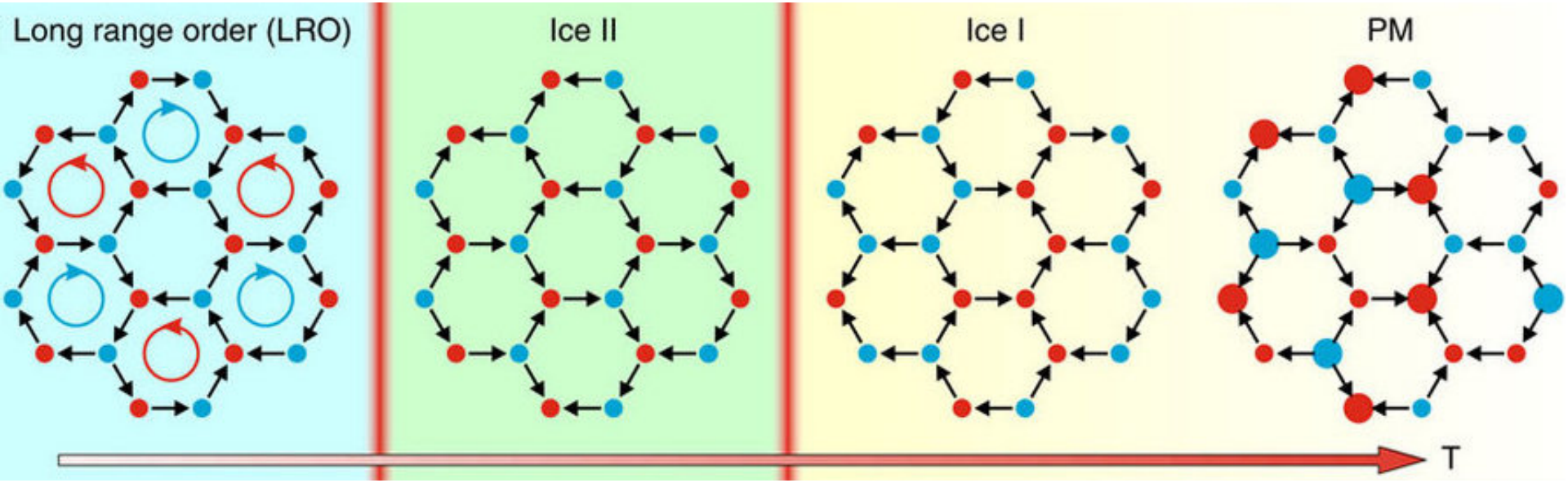
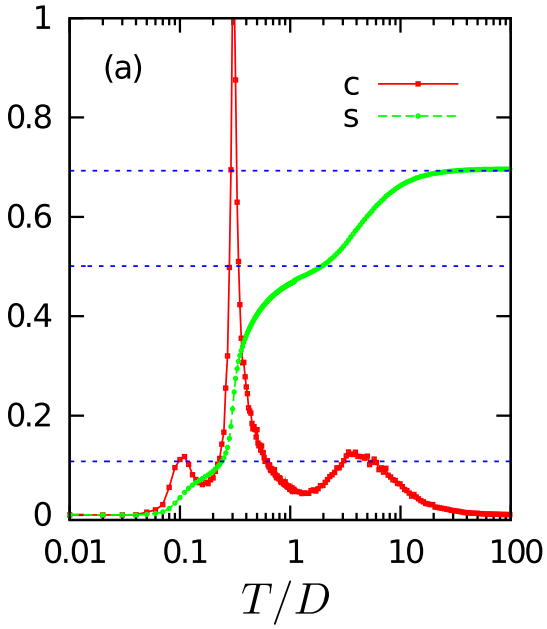
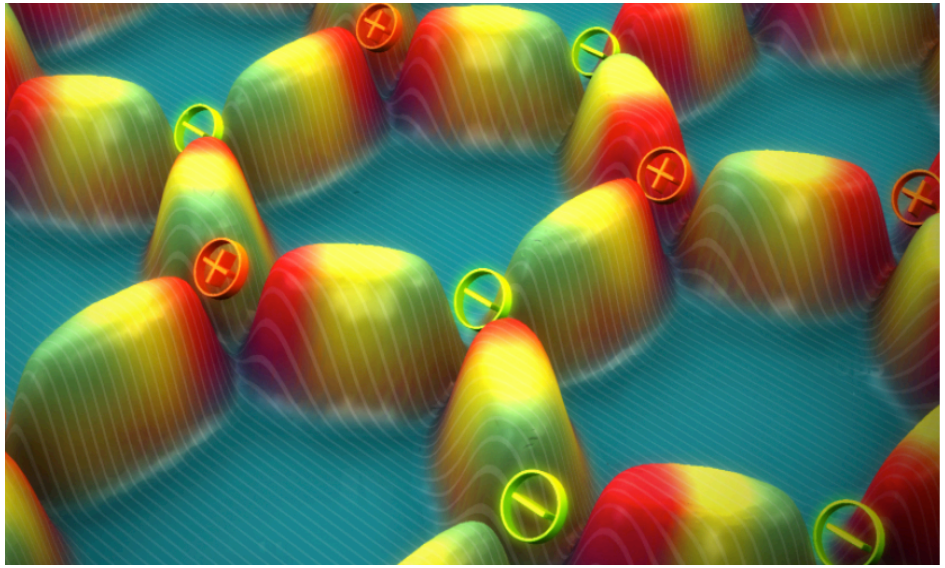
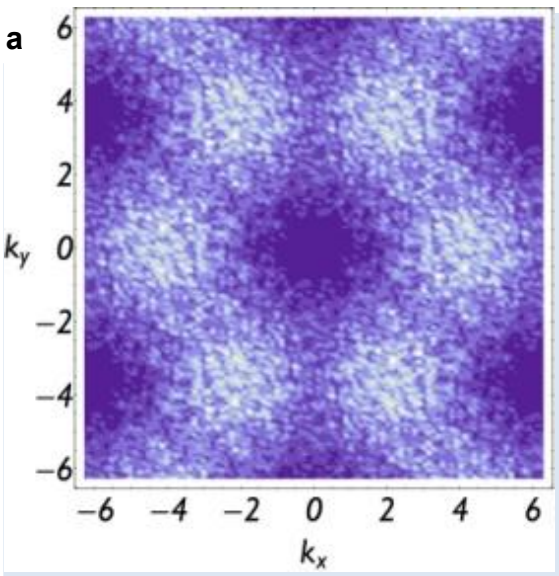
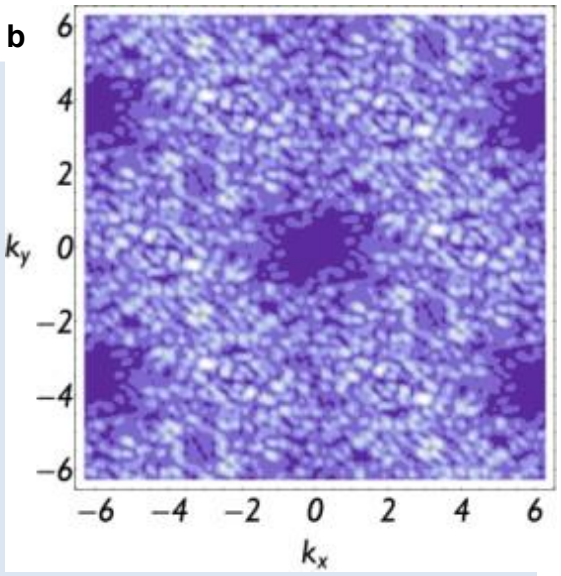

Long range order (LRO)
Ice II
Ice I
PM
T

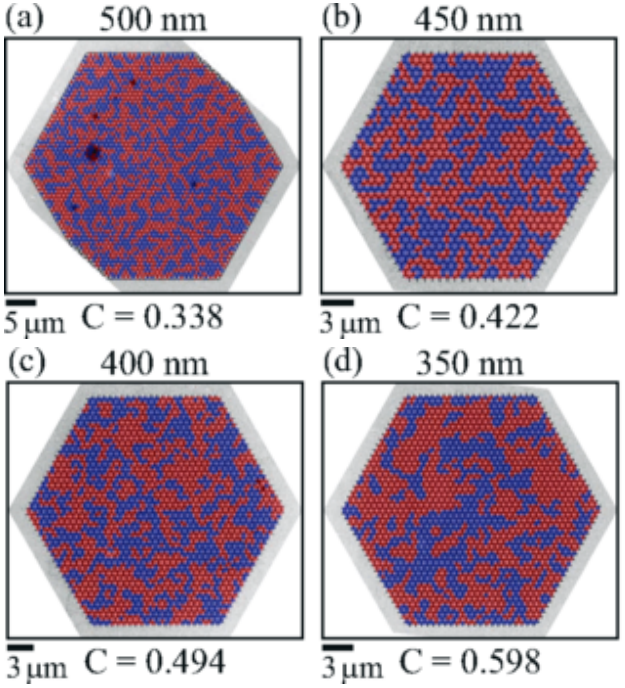

(a)
c
s
1
0.8
0.6
0.4
0.2
0
0.01
0.1
1
10
100
T/D

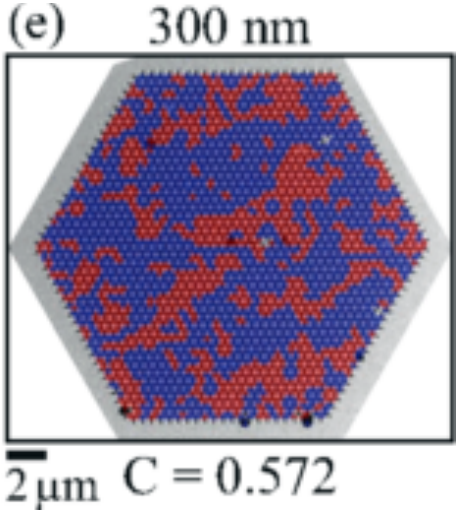


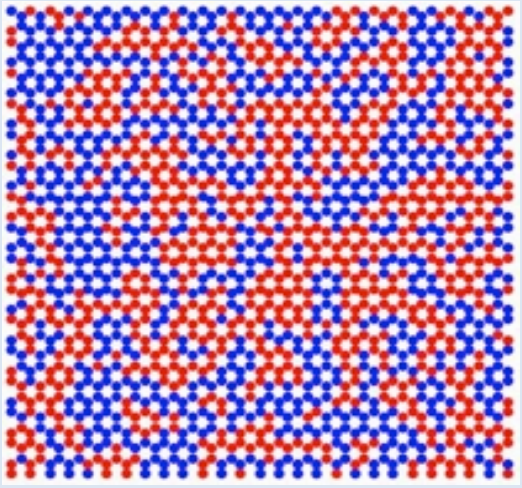
Artificial Spin ice, Emergence, Subtle Exotic States

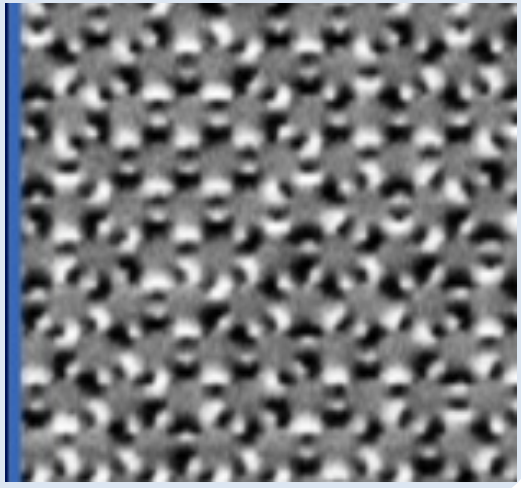








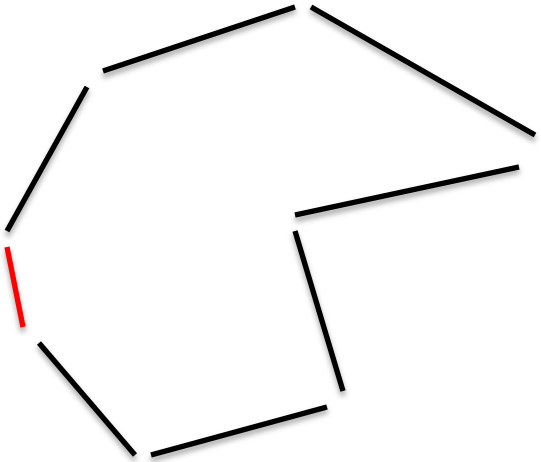




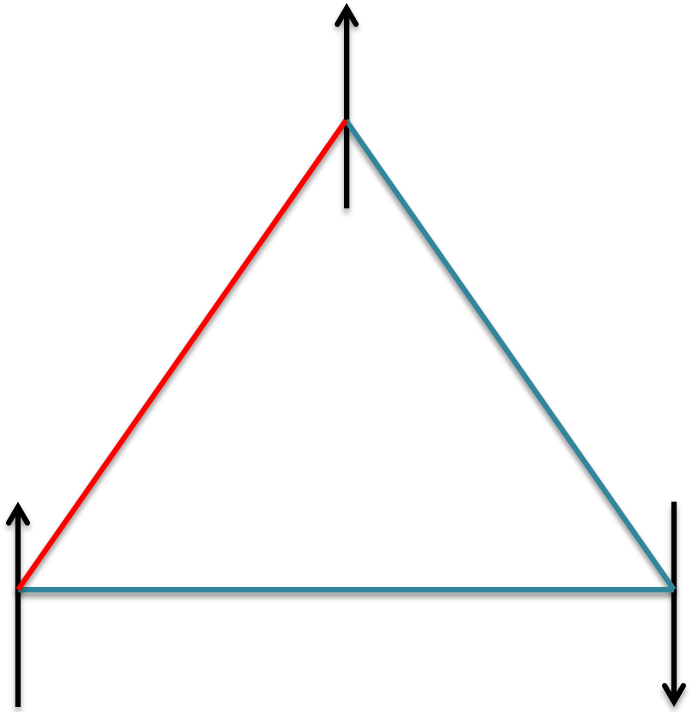
Nature 500, 553–557 (2013)

Phys. Rev. B 91, 224406 (2015)

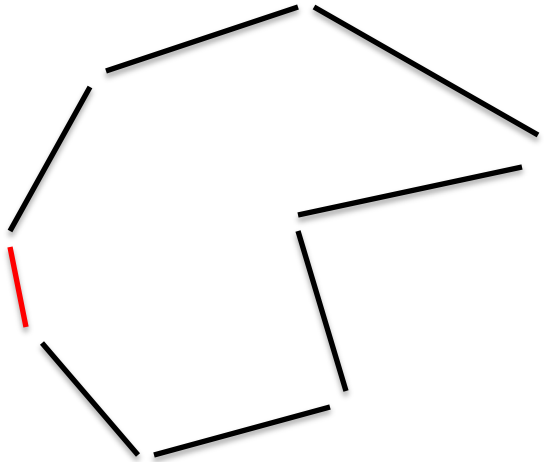
Geometric Frustration



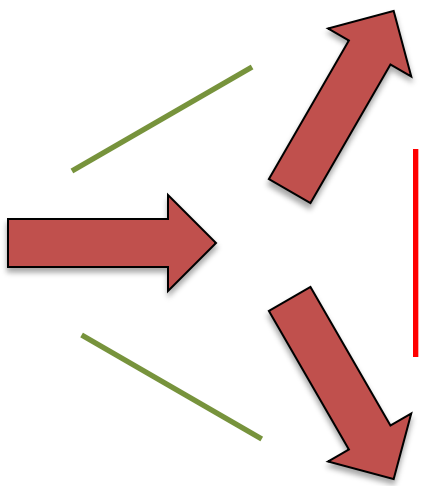
Geometric Frustration

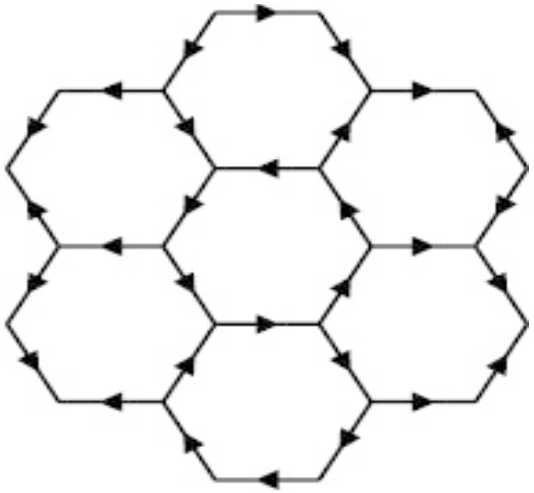


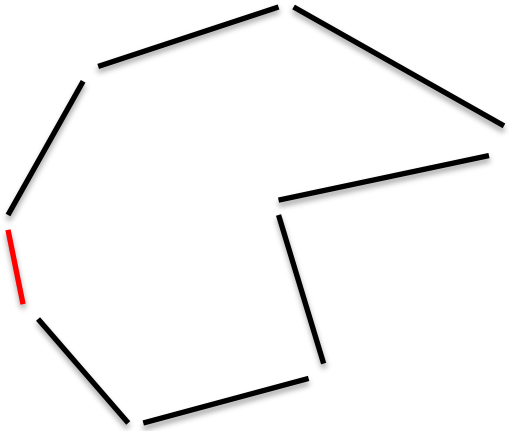
G. H. Wannier Phys. Rev. 79, 357 (1950)

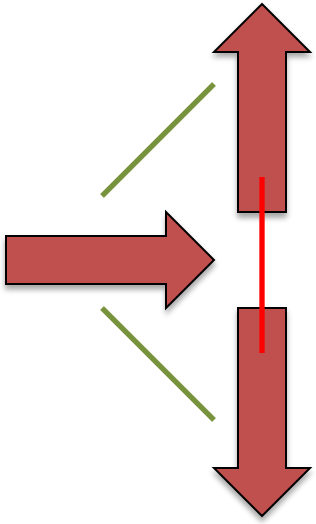


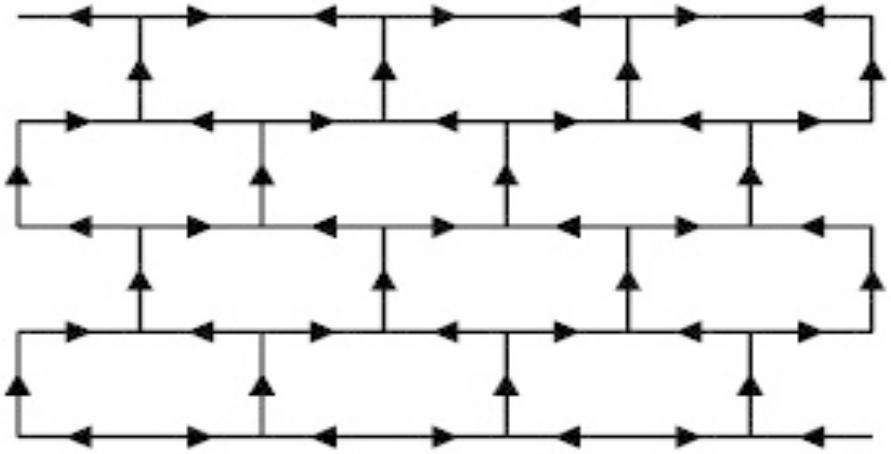
Trivial Ice Manifolds



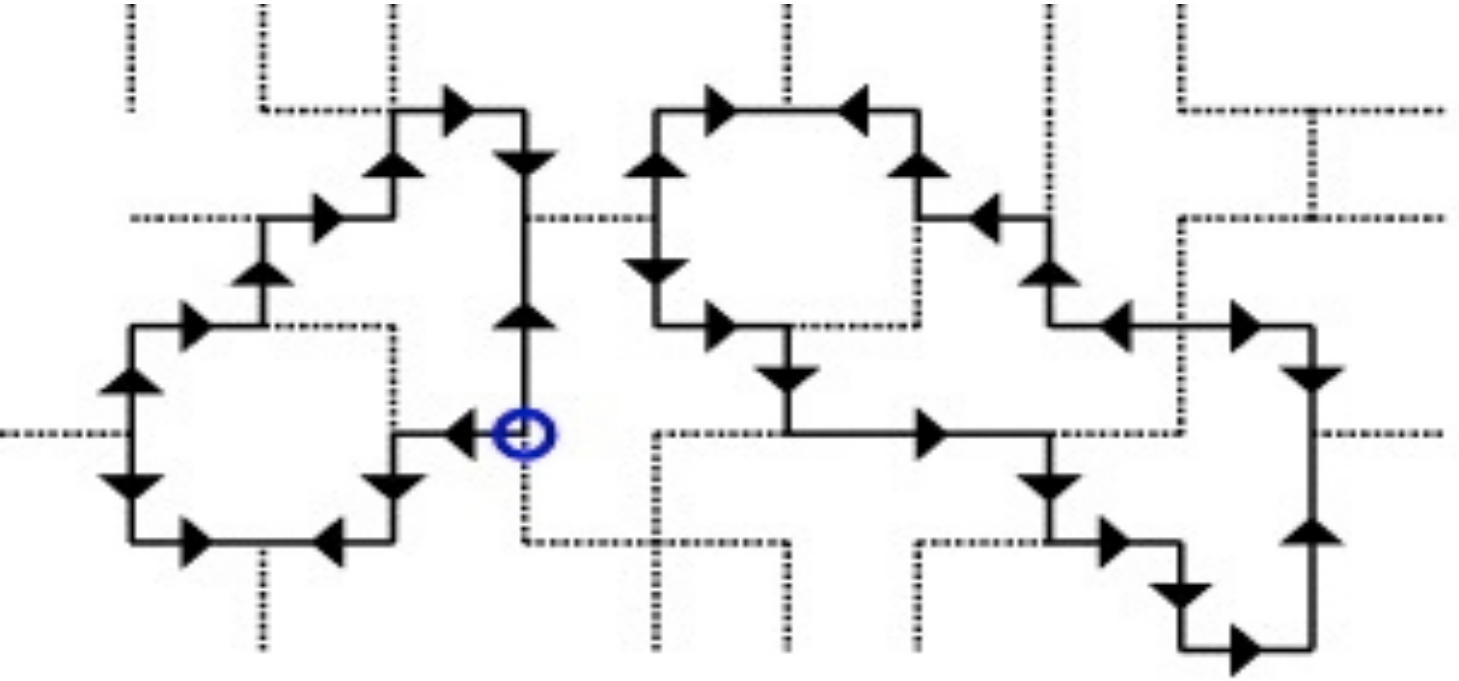


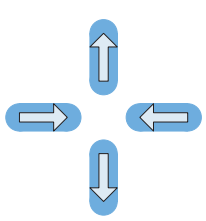






Non-Trivial Ice Manifolds





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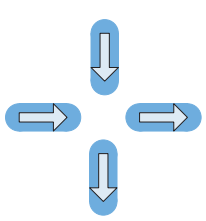

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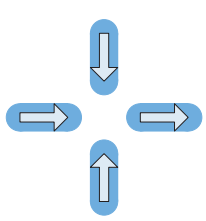

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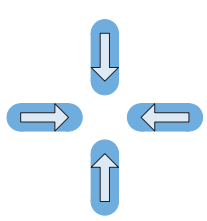

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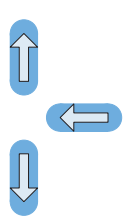

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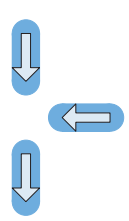

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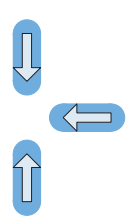

Type III_3 (2)

Type I_2 (2)

Type II_2 (2

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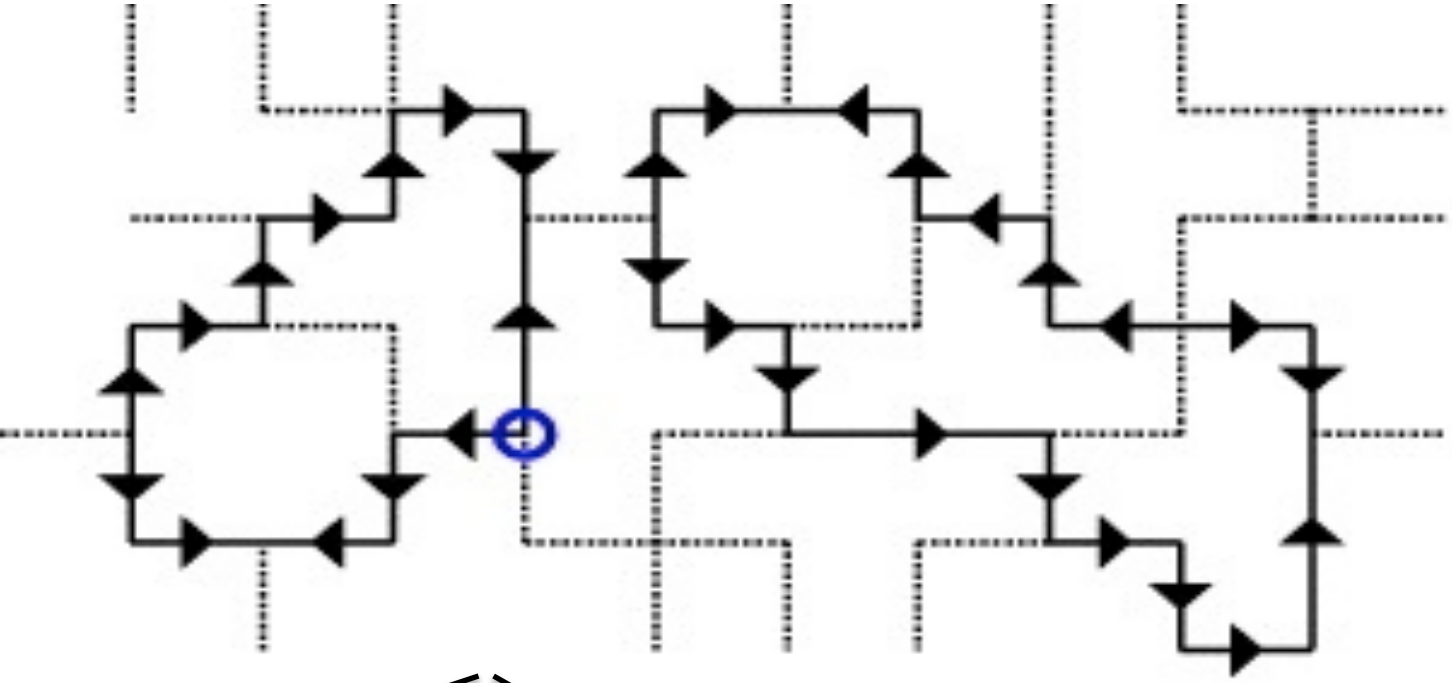
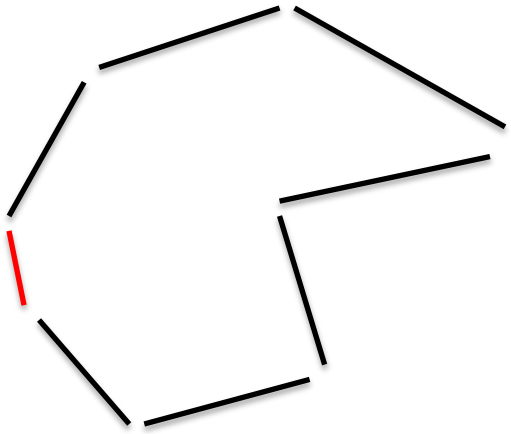
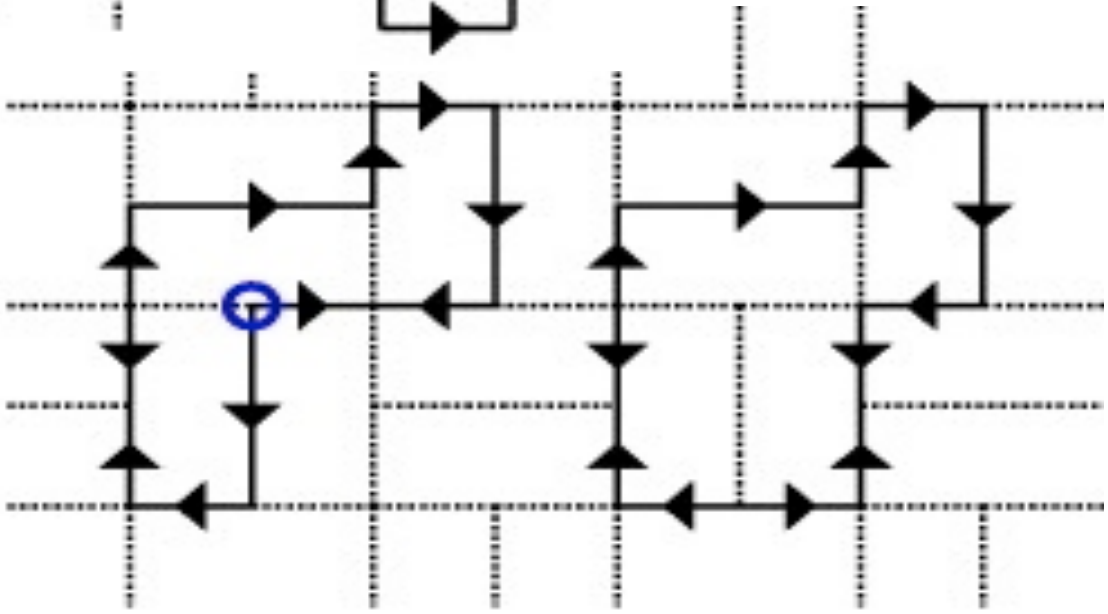
Non-Trivial Ice Manifolds

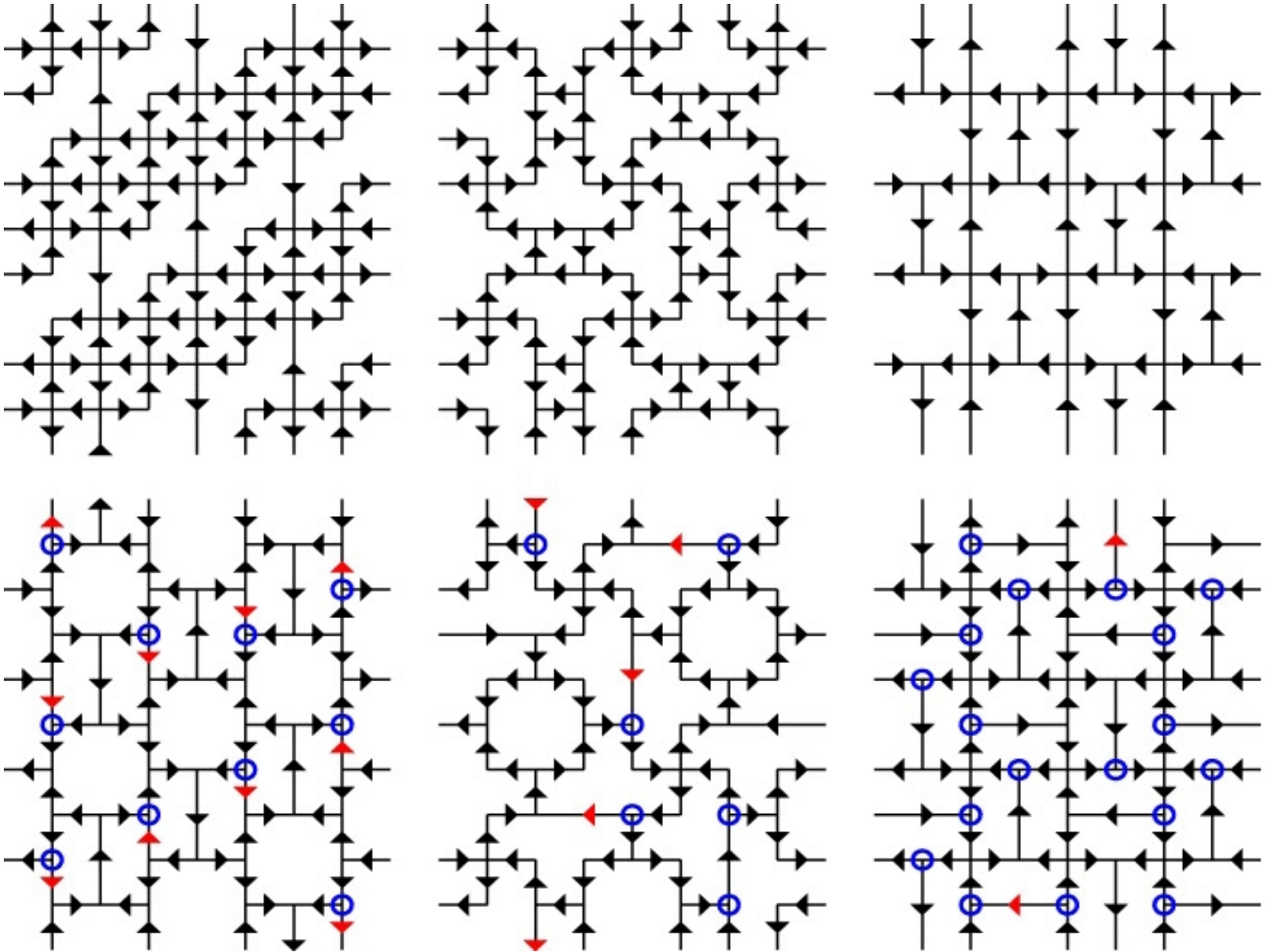




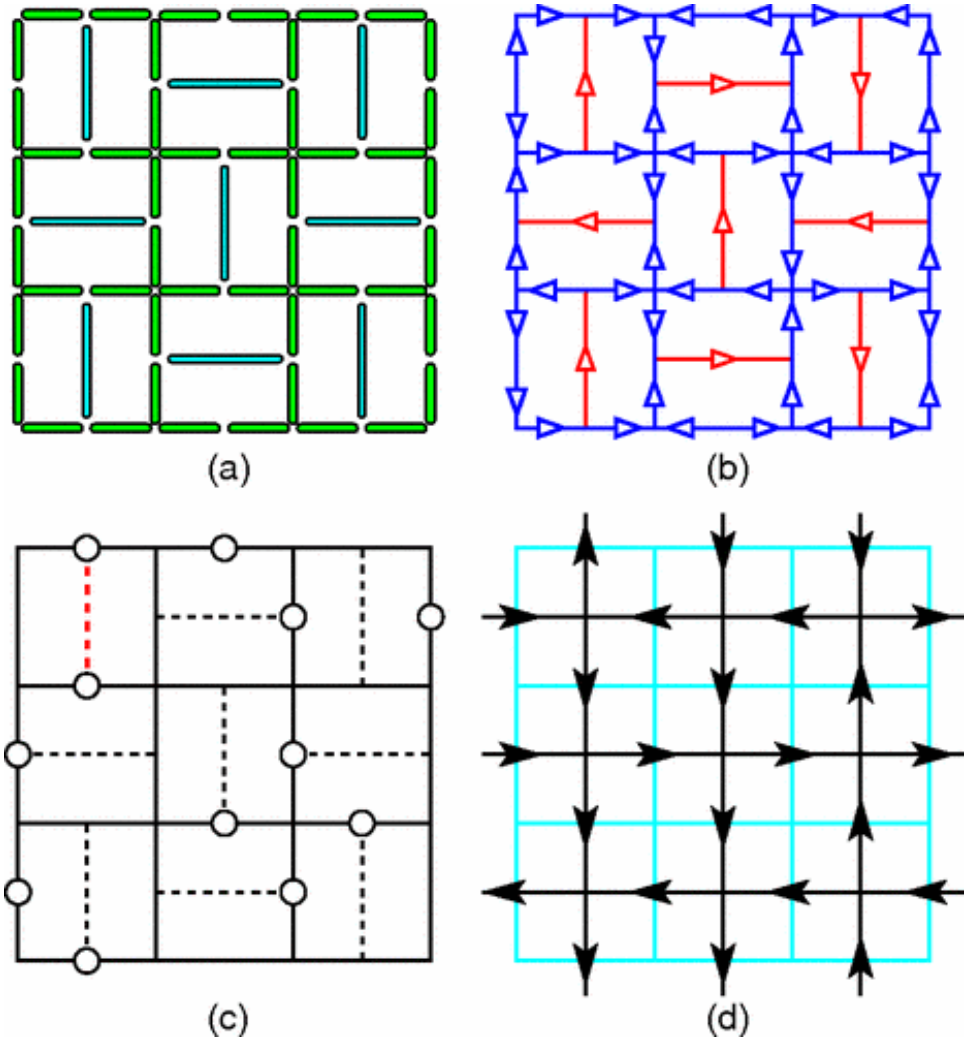


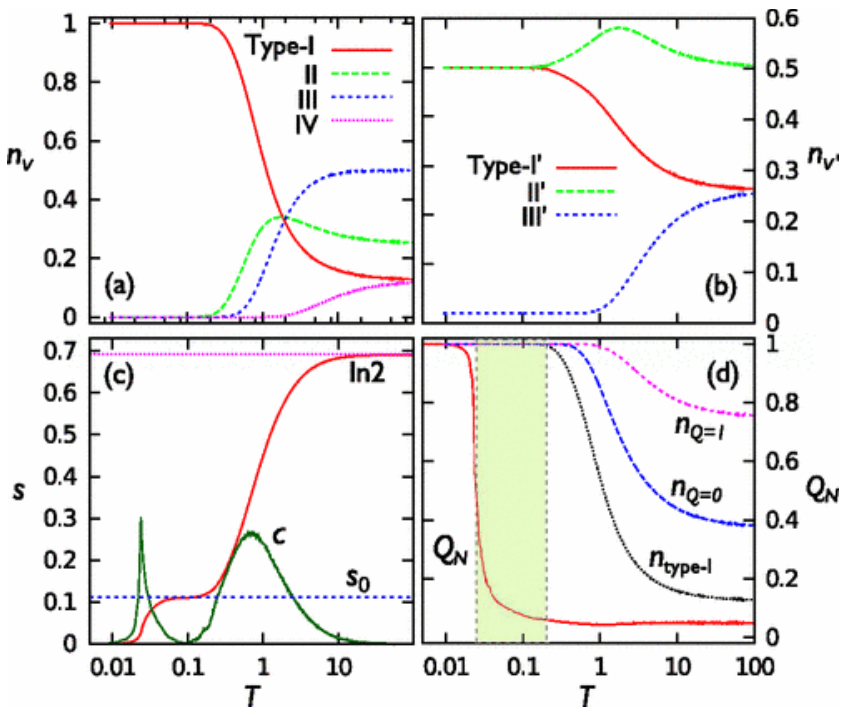
New Journal of Physics
15 (4), 045009 2013

Non-Trivial Ice Manifolds



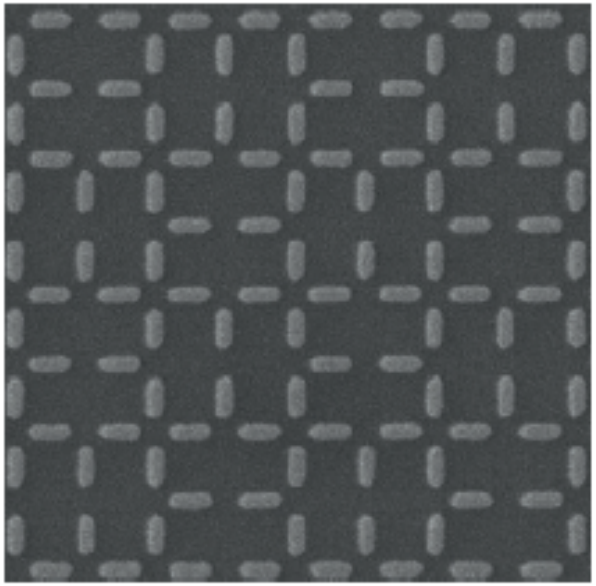
Shakti Ice

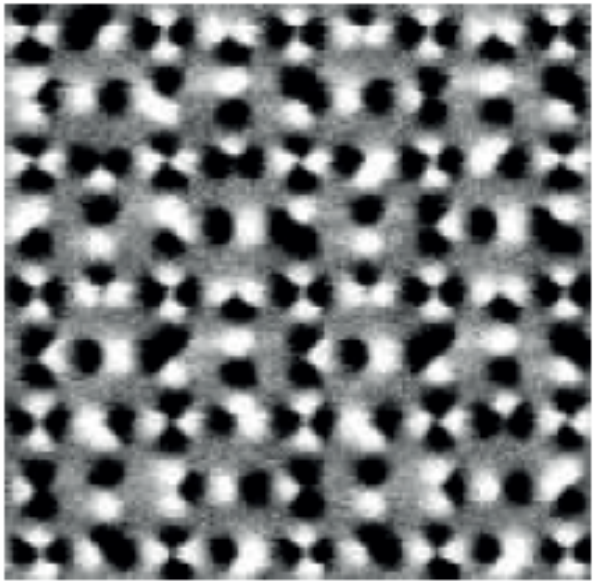


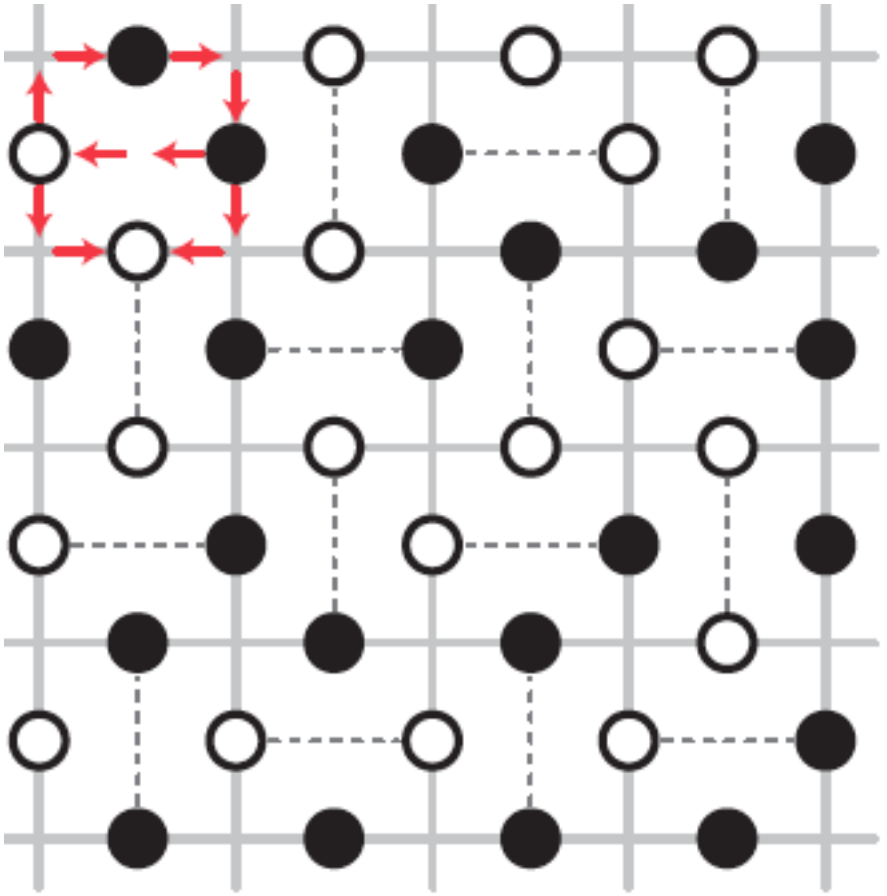


Physical Review Letters 111, 177201 2013

Shakti Ice

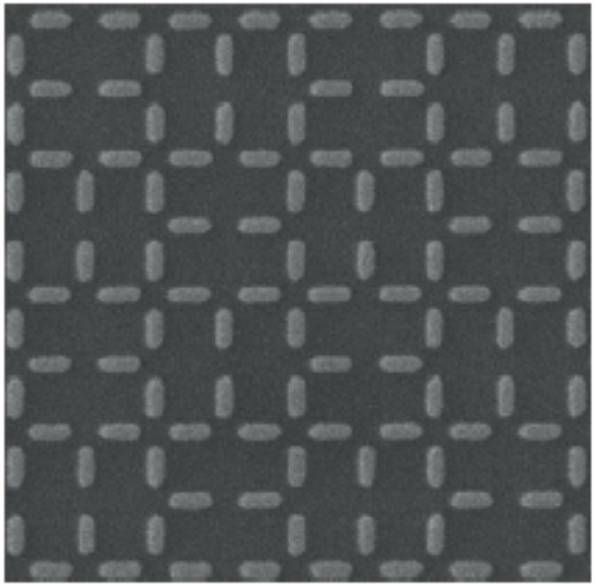


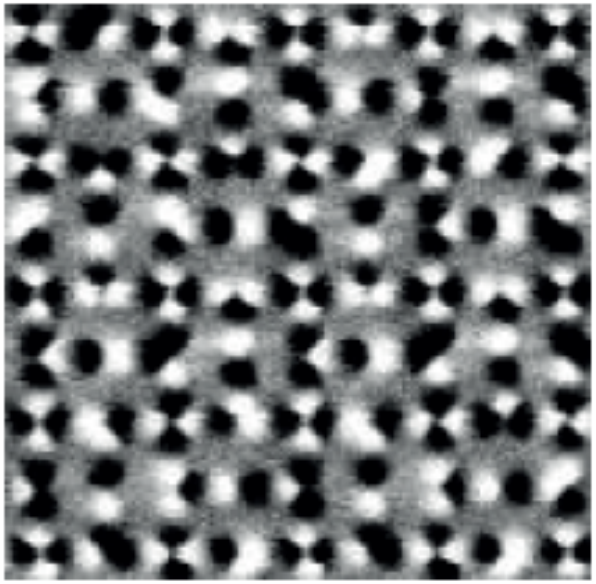


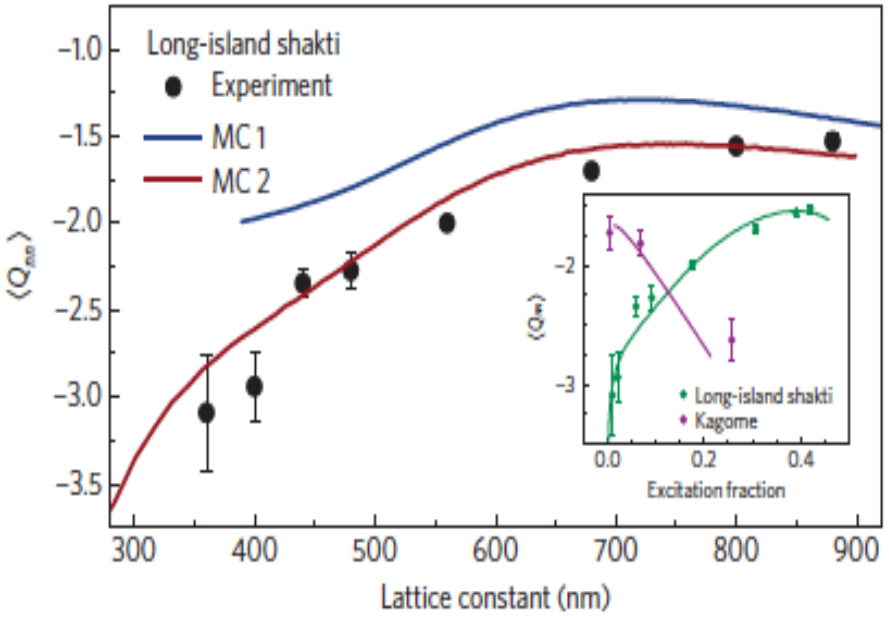


Nature Physics 10, 670–675 (2014)

Shakti Ice

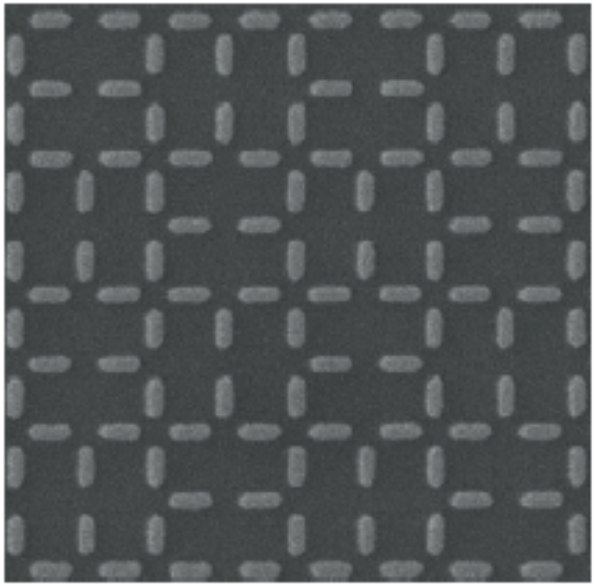


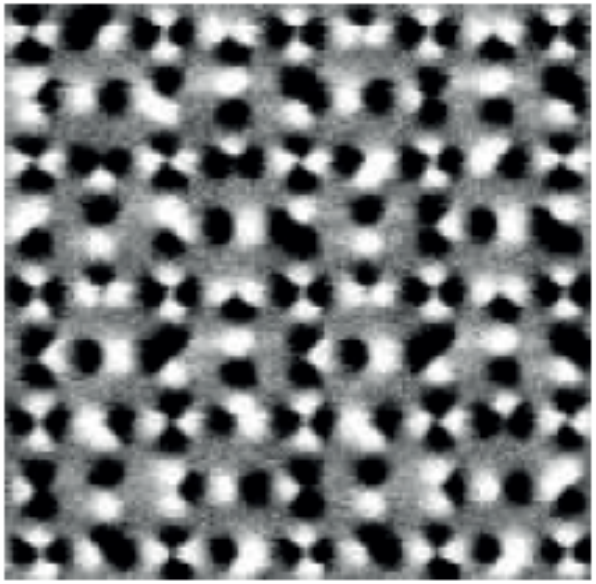


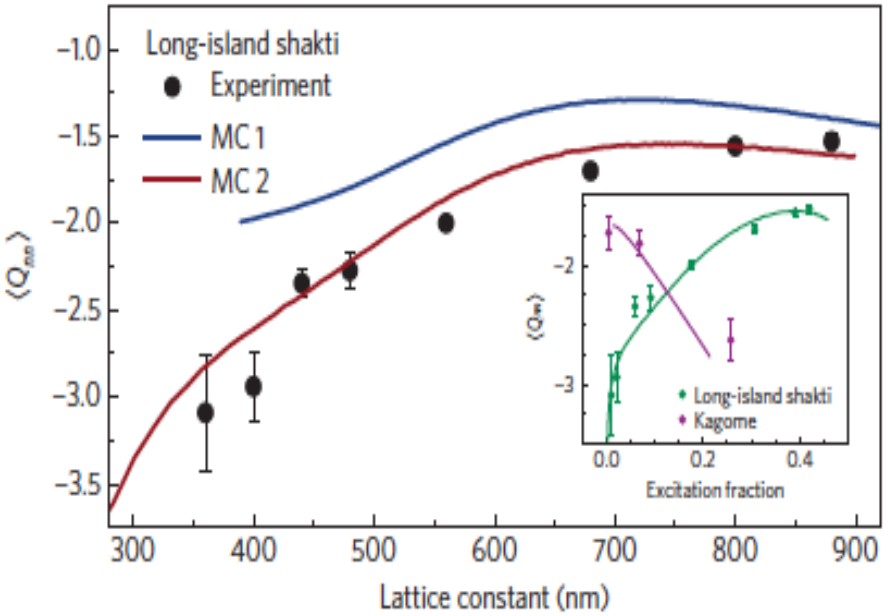

Long-island shakti
Experiment
MC 1
MC 2
⟨Q_nn⟩
−1.0
−1.5
−2.0
−2.5
−3.0
−3.5
300
400
500
600
700
800
900
Lattice constant (nm)
⟨Q_nn⟩
−2
−3
Long-island shakti
Kagome
0.0
0.2
0.4
Excitation fraction

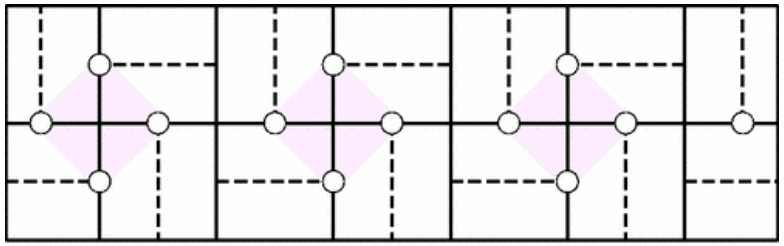
New Theoretical Directions: DESIGNING EMERGENCE

Los Alamos NATIONAL LABORATORY EST. 1943

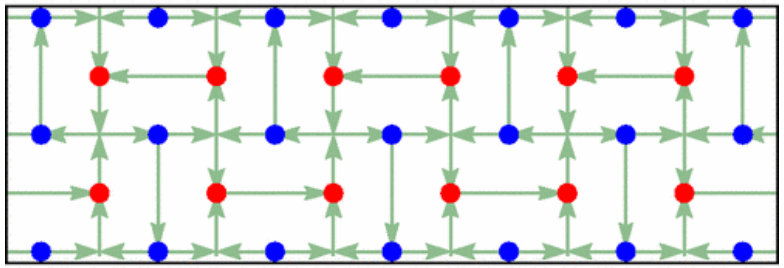






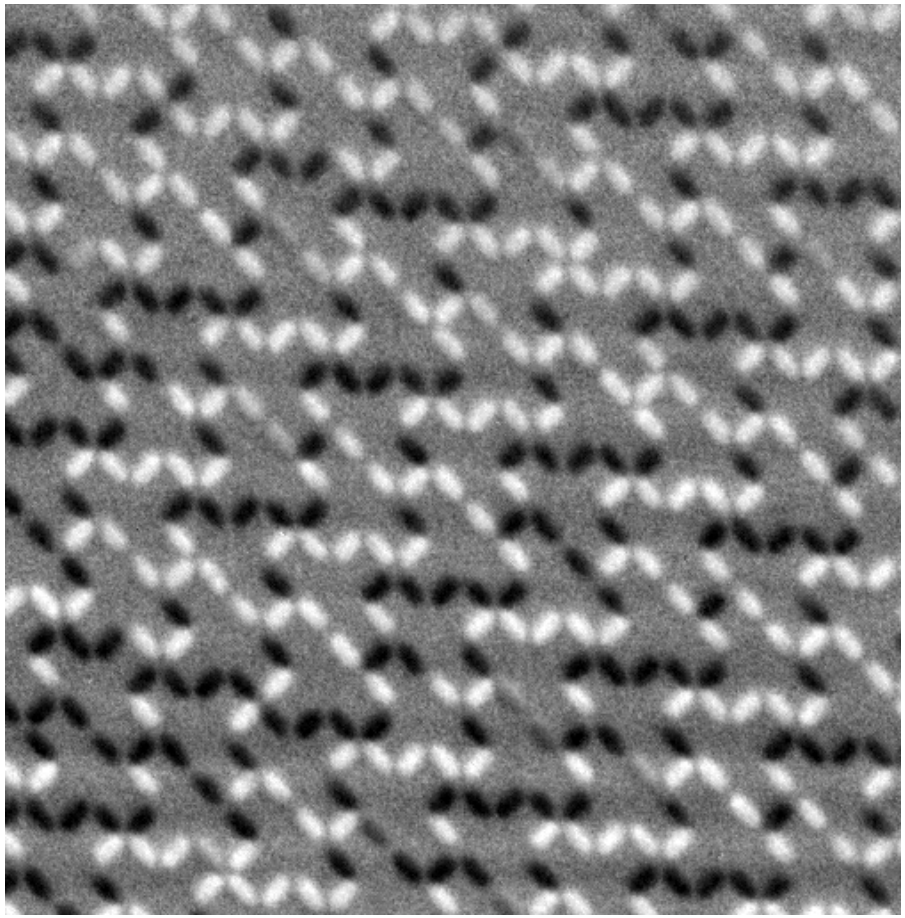


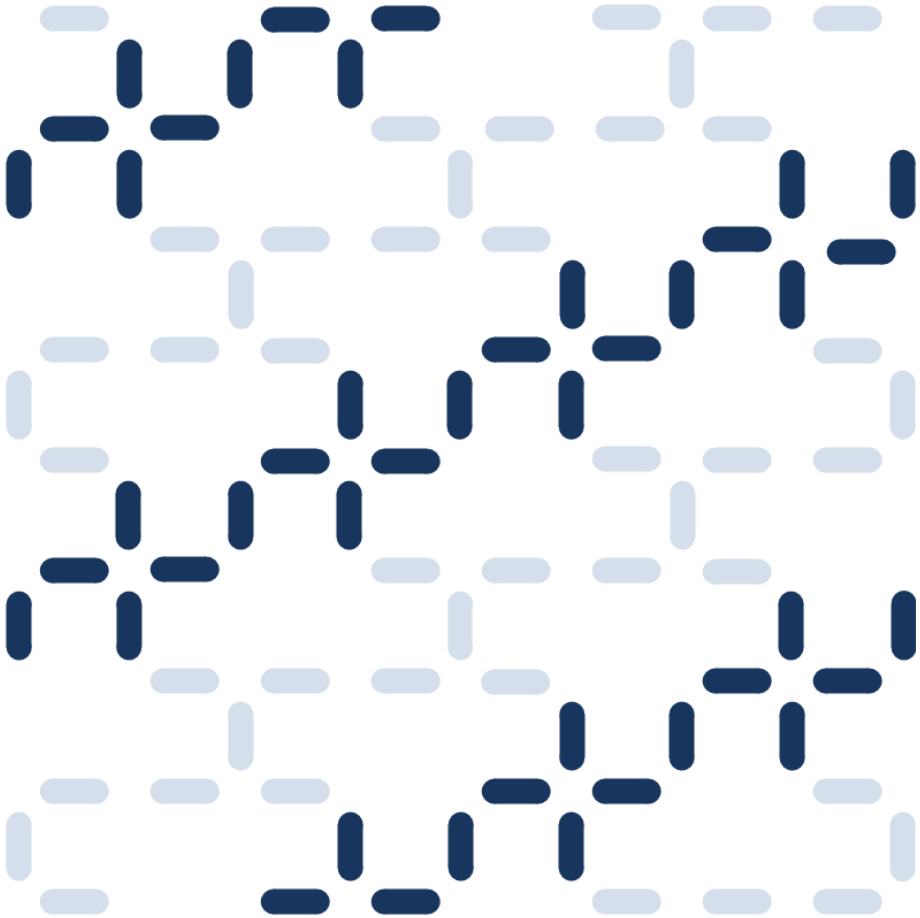
(a)



(b)

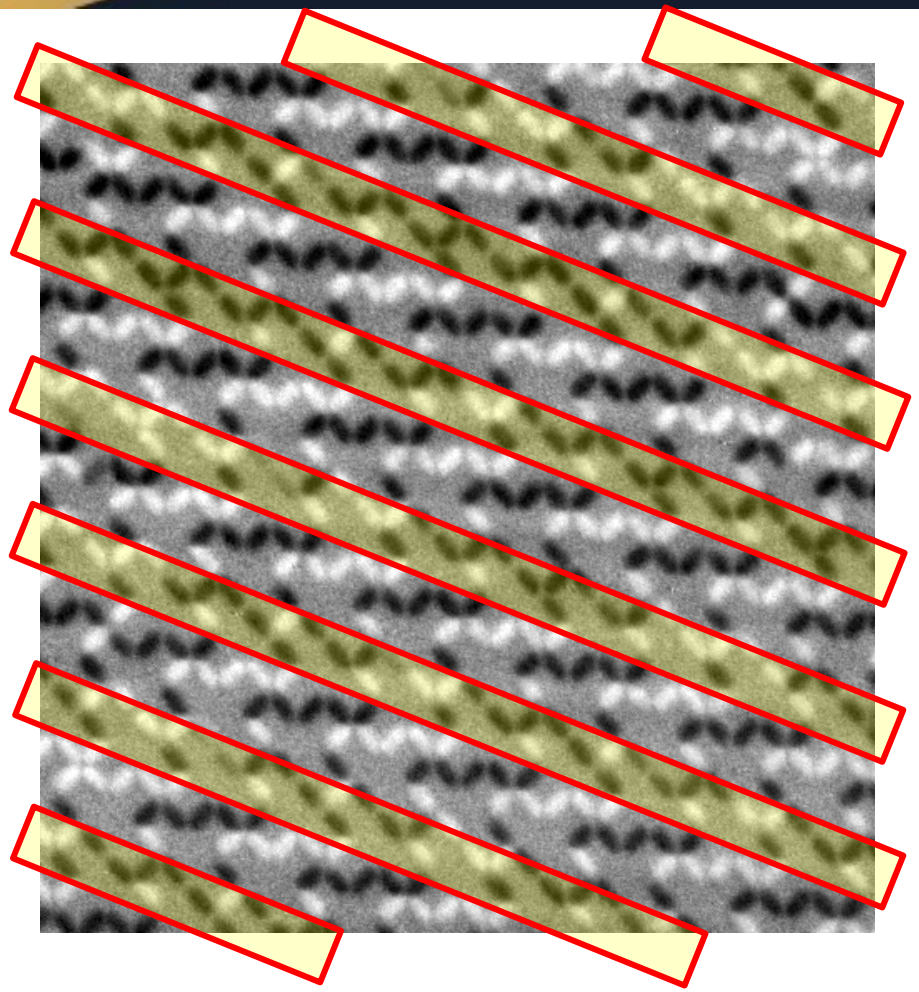
Tetris Ice

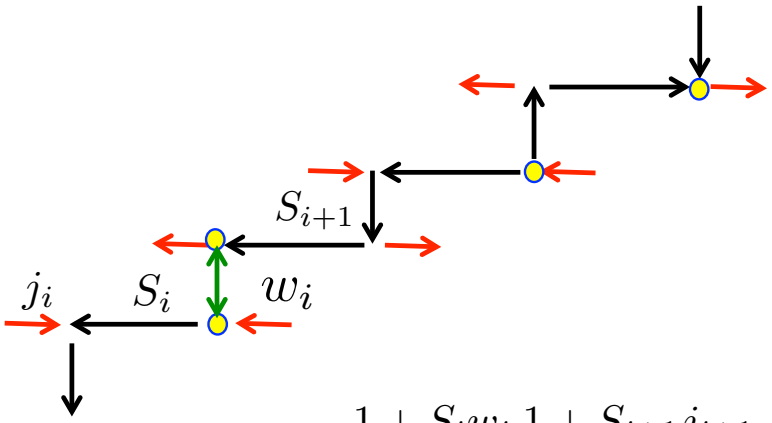




Nature Physics (2016) doi:10.1038/nphys3520

Tetris Ice





$$n_{\mathrm{FVS}}[\{S_i\}] = \sum_i \frac{1+S_i w_i}{2}\frac{1+S_{i+1} j_{i+1}}{2}$$

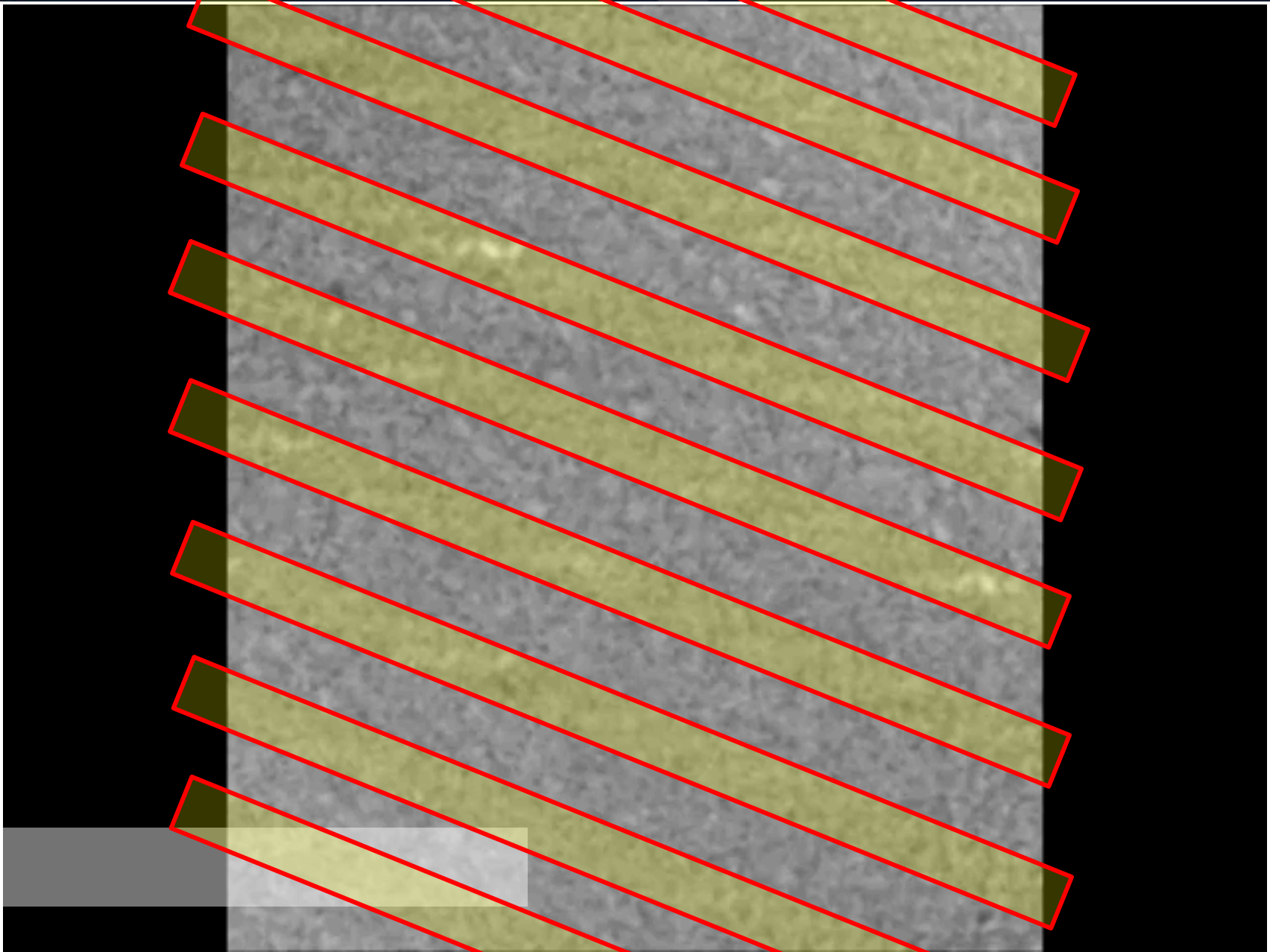
$$= \frac{1}{4}\sum_i \left[1 + S_i S_{i+1} w_i j_{i+1} + S_i\left(w_i + j_i\right)\right]$$

$$= \frac{1}{4}\sum_i \left[1 + S_i S_{i+1}\right]$$

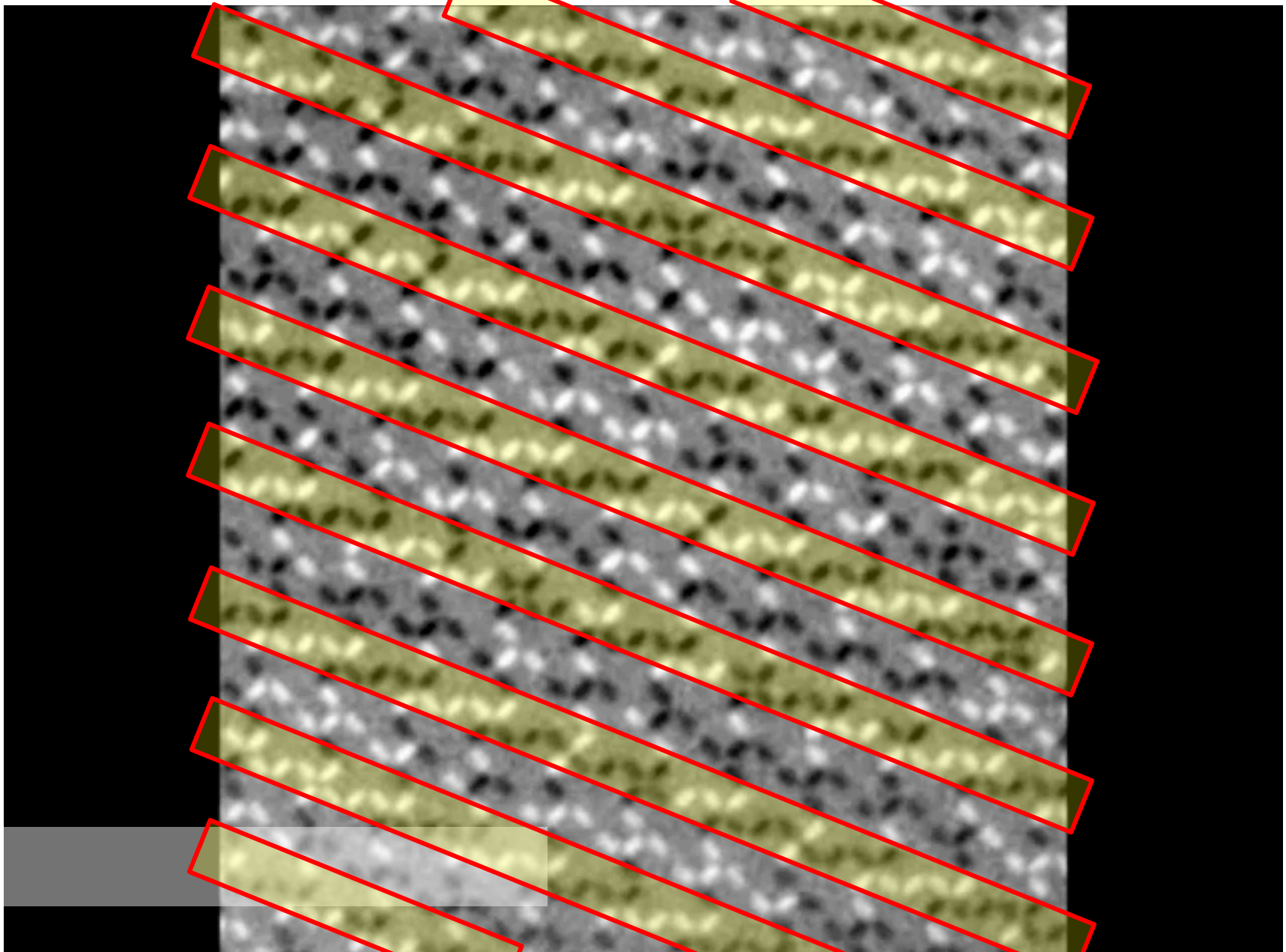
$$W = \sum_{\{S_i\}} 2^{n_{\mathrm{FVS}}[\{S_i\}]} = 2^{\frac{N_S}{4}} \sum_{\{S_i\}} \exp\left(\beta J \sum_i S_i S_{i+1}\right)$$

$$\beta J = \frac{\ln 2}{2}$$

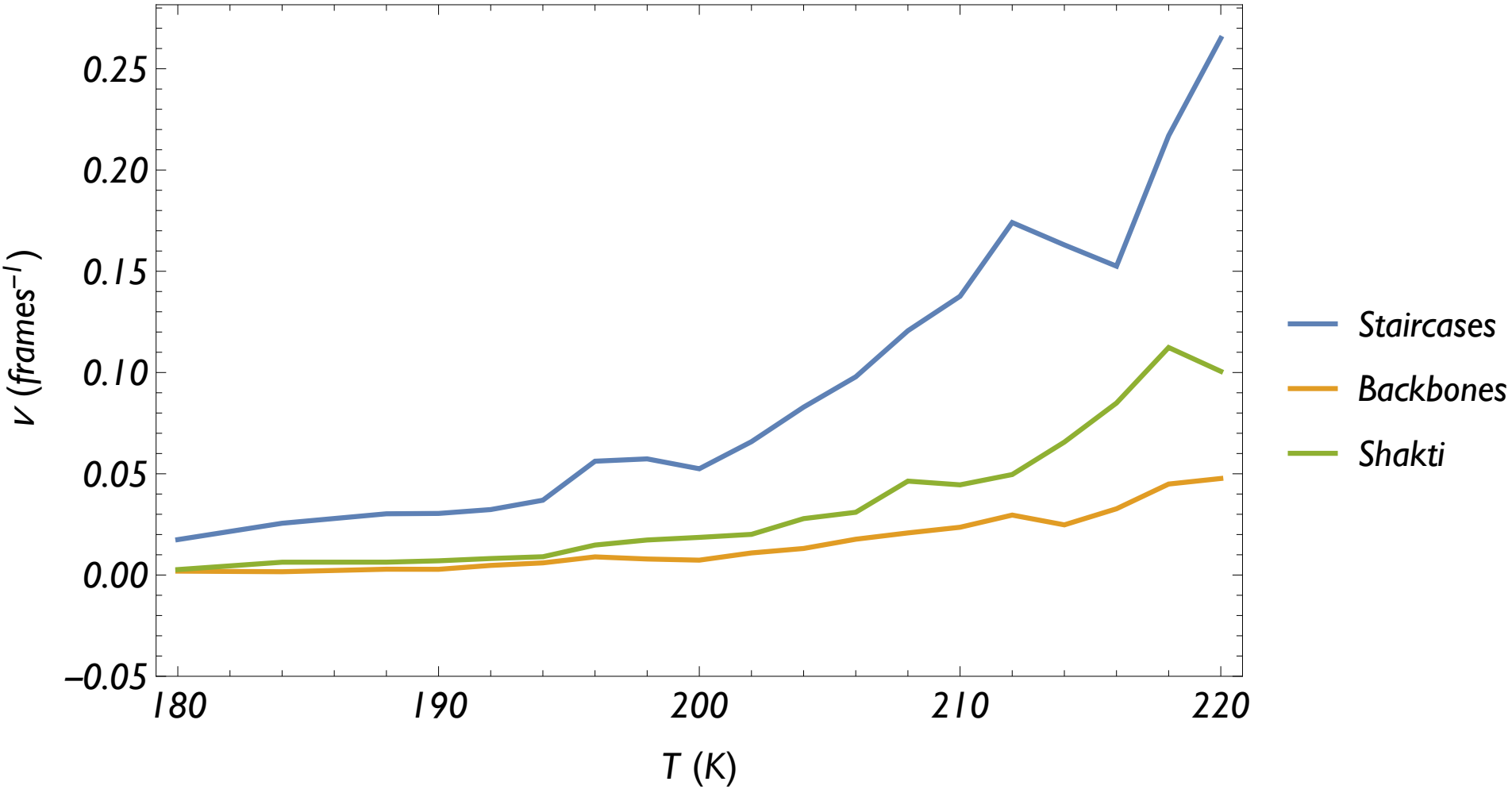
Tetris Ice



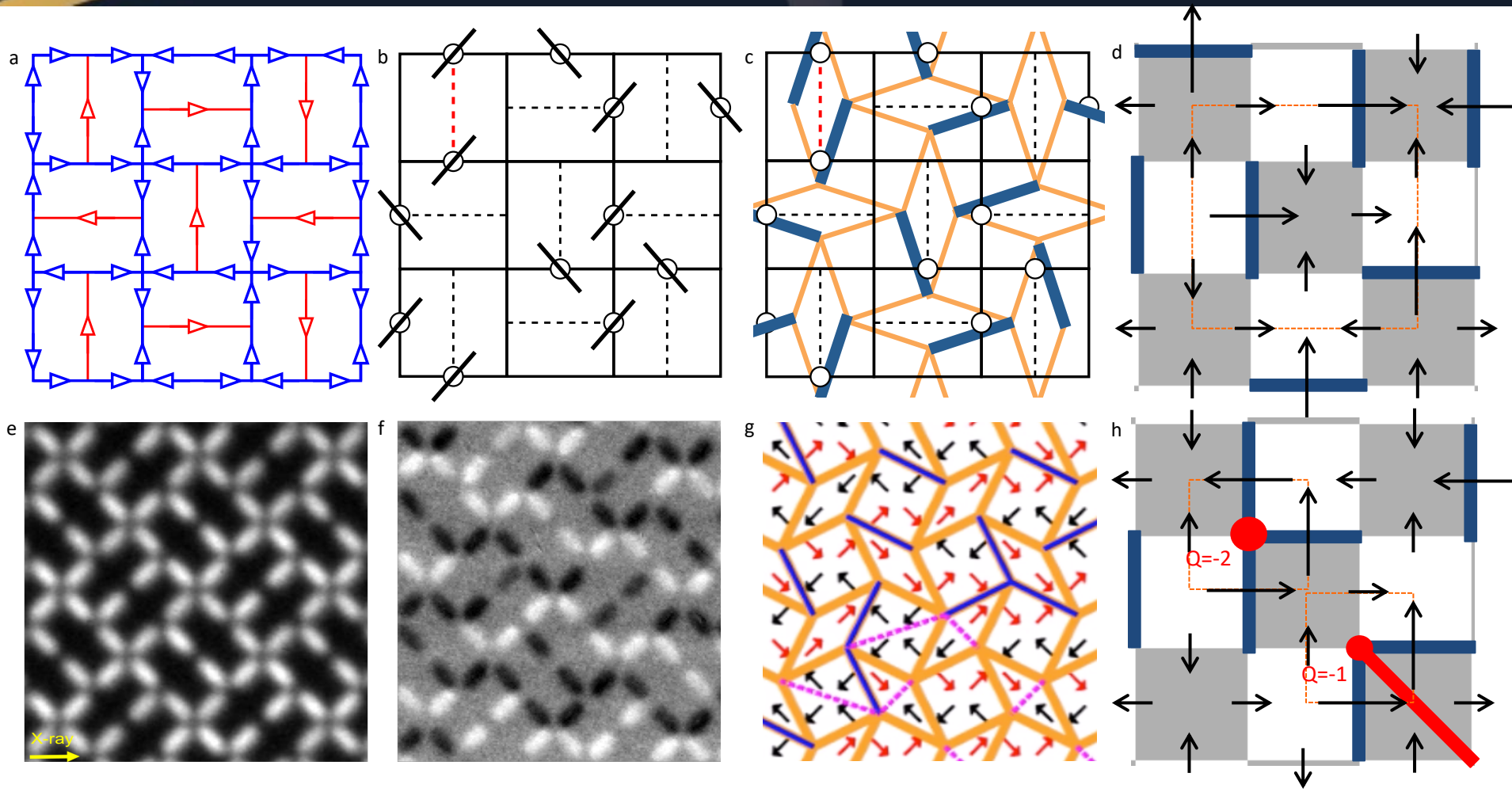
Tetris Ice



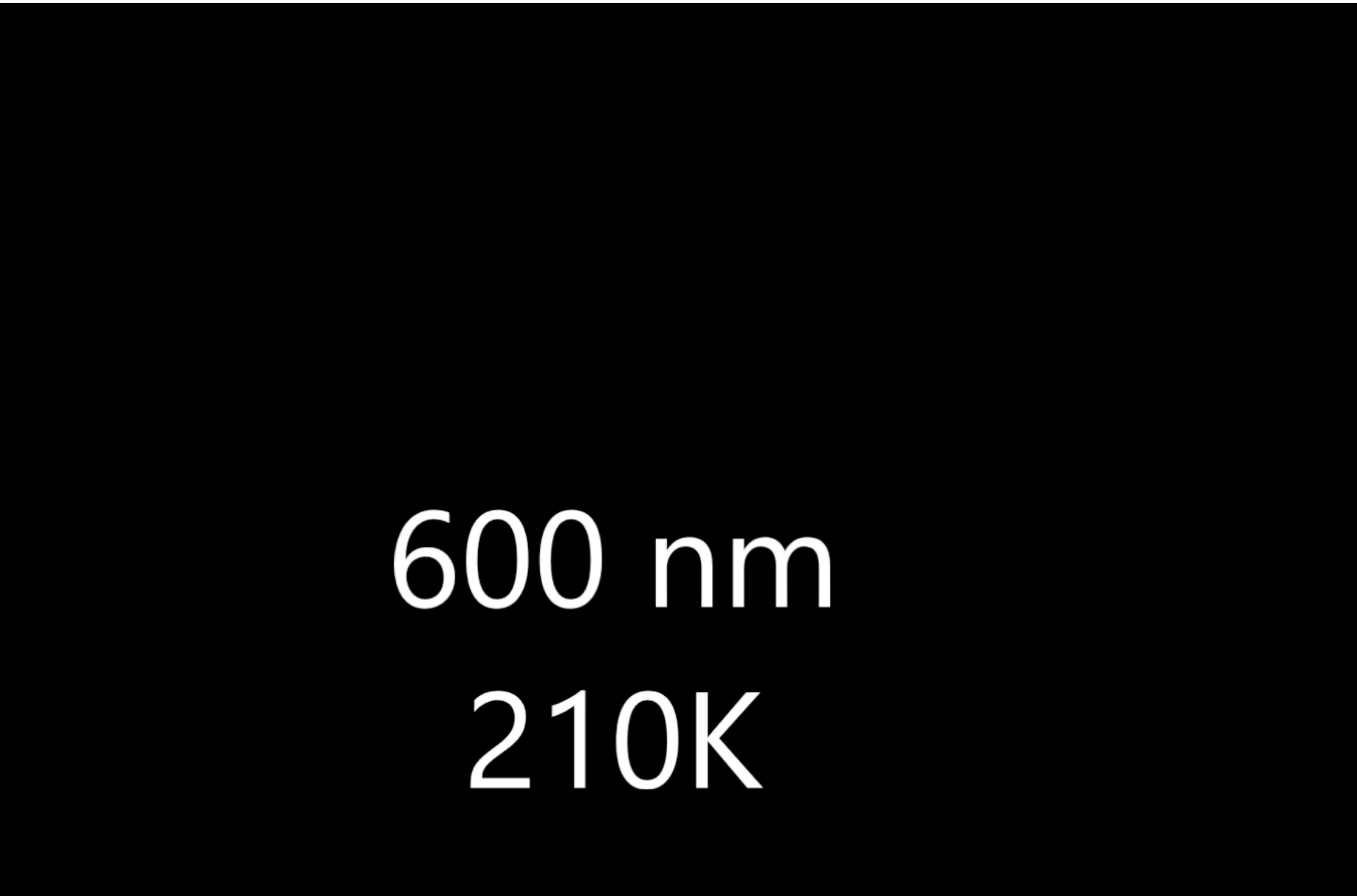
Tetris Ice


0.25
0.20
0.15
0.10
0.05
0.00
−0.05
ν (frames⁻¹)
180
190
200
210
220
T (K)
Staircases
Backbones
Shakti

Shakti Kinetics

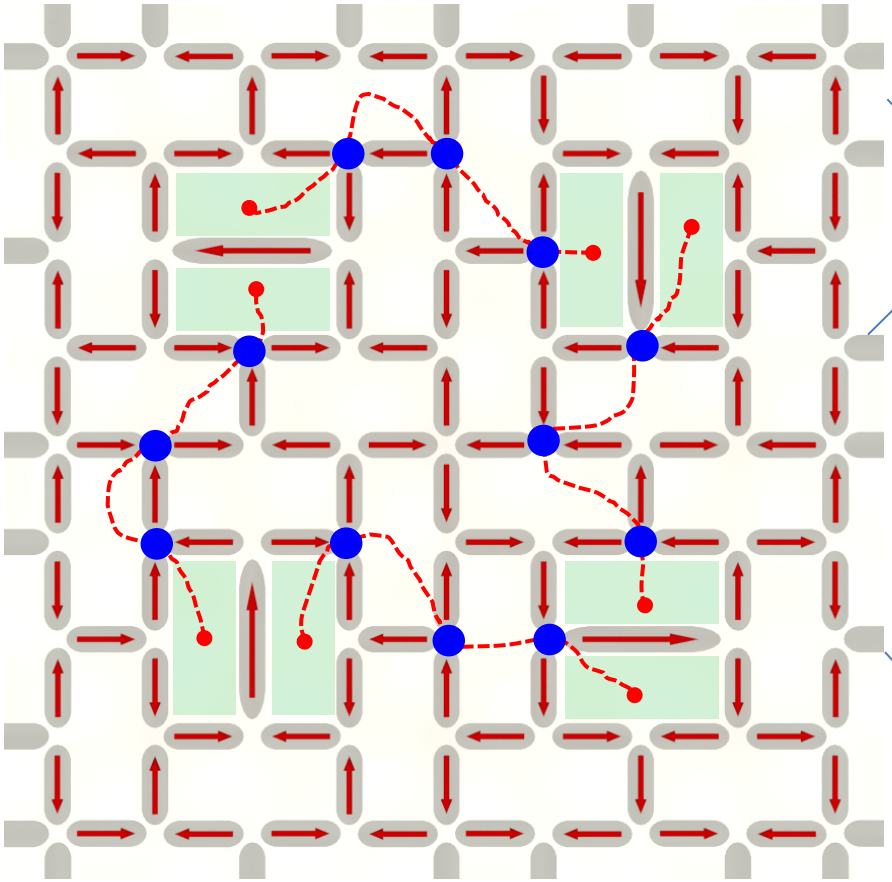


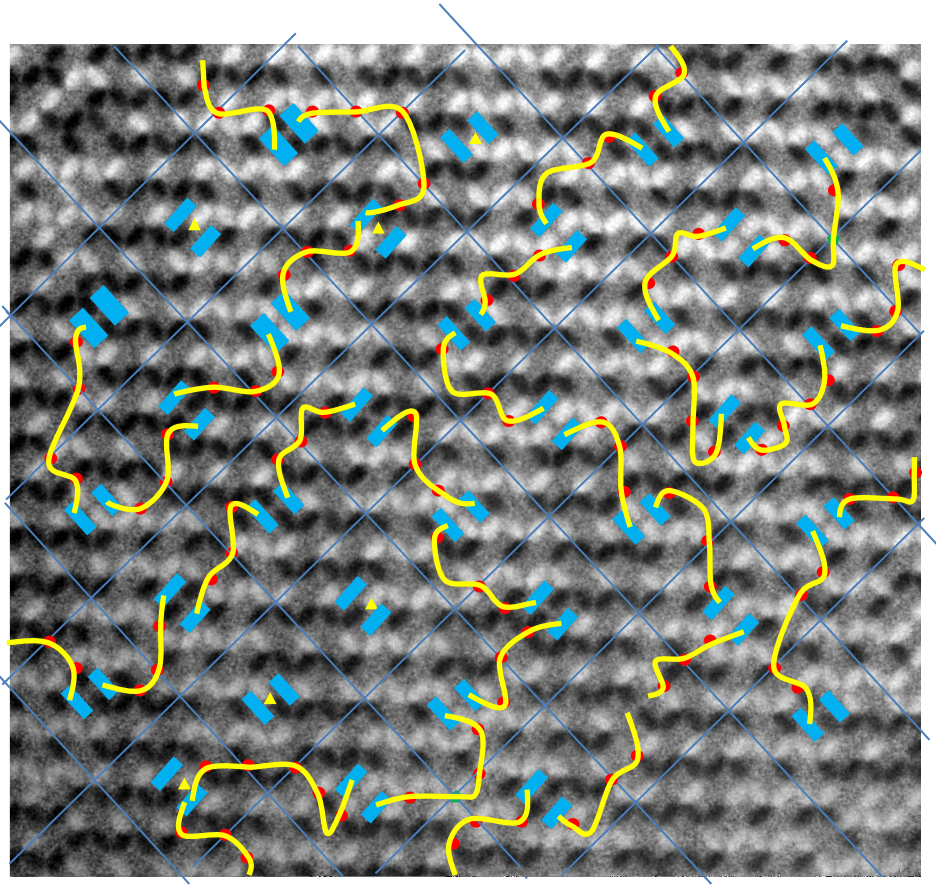
Shakti Kinetics



Shakti Kinetics

Future: Non-Trivial Ice Manifolds and Topology





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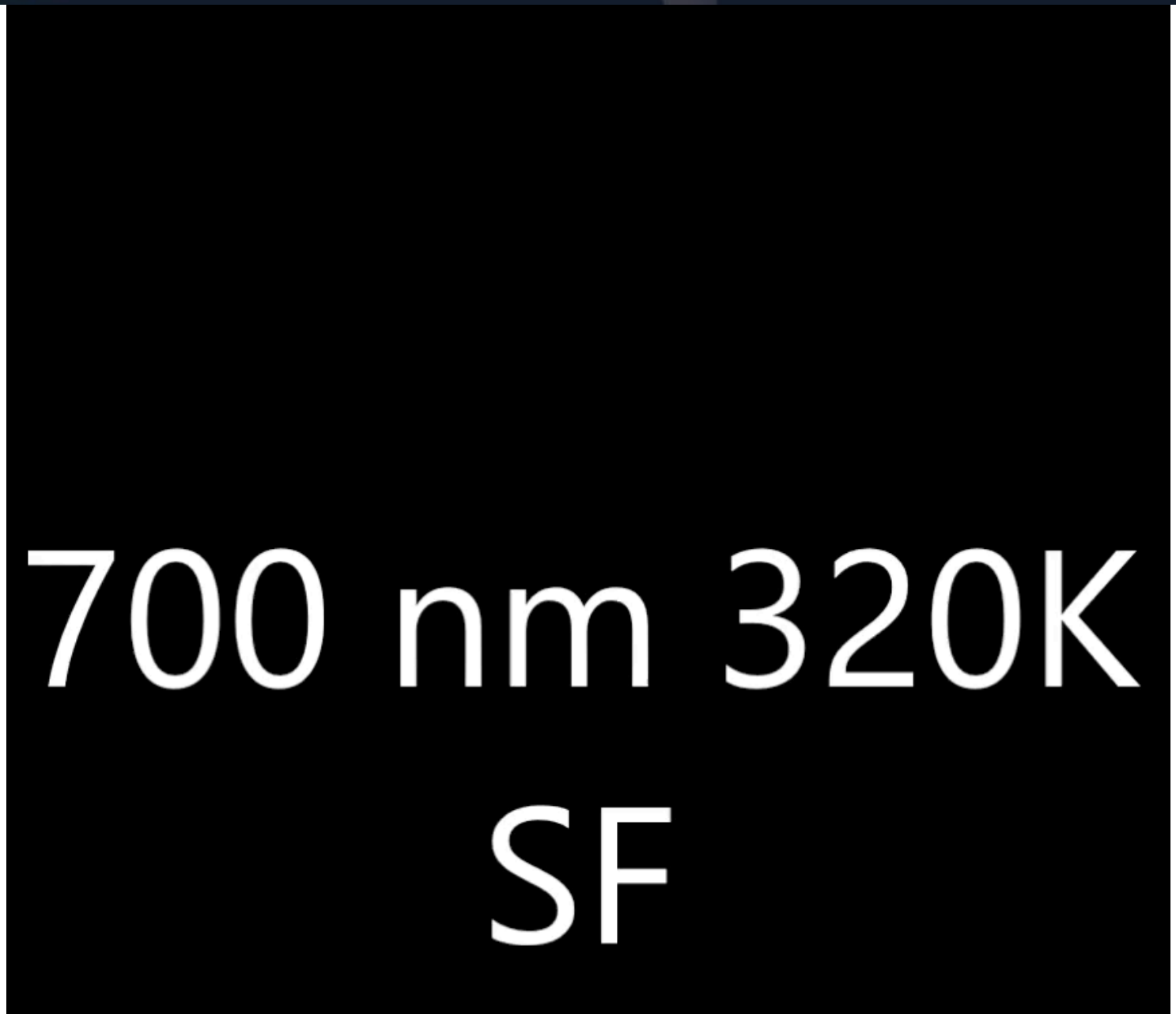
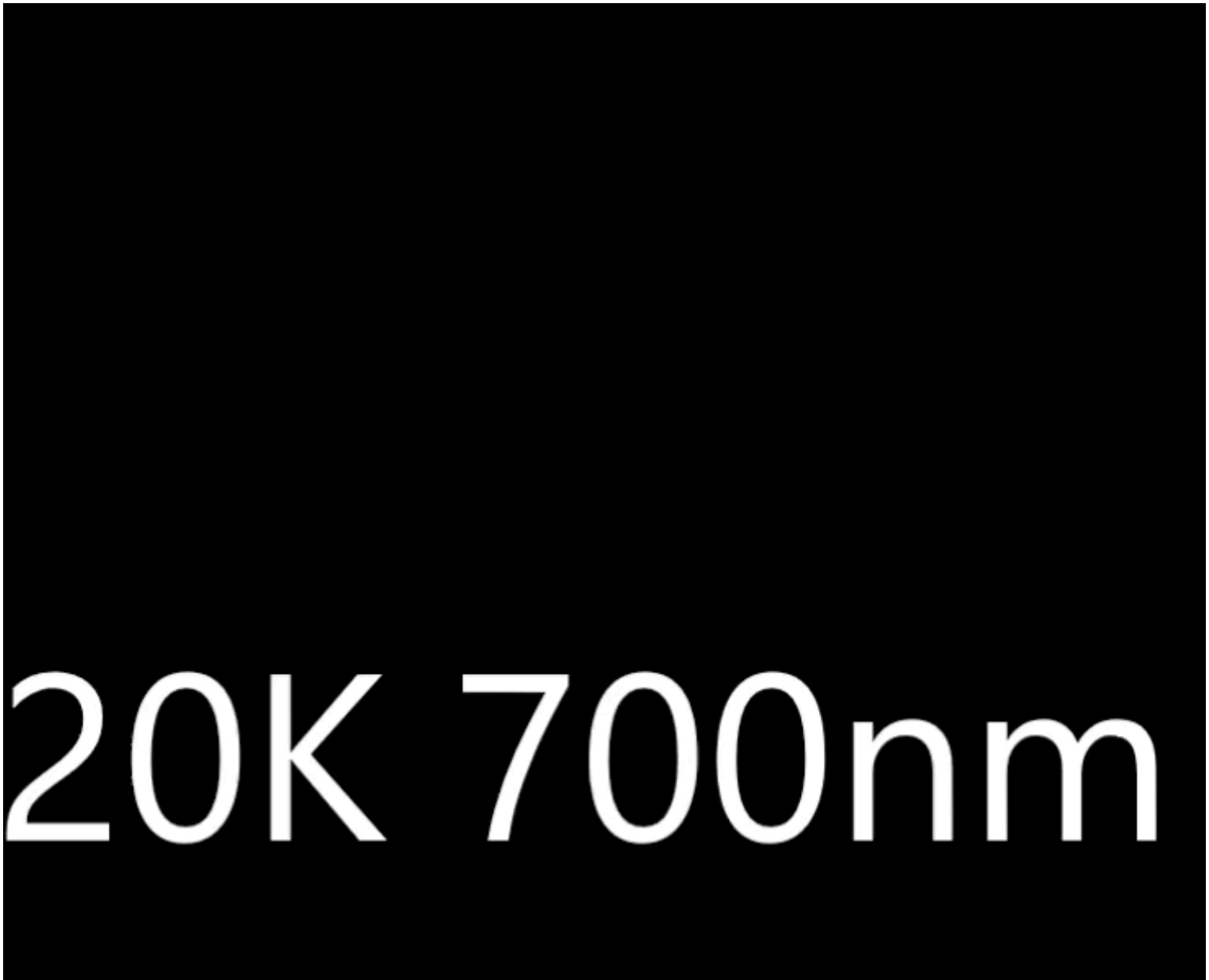
Future: Non-Trivial Ice Manifolds and Topology



Future: Non-Trivial Ice Manifolds and Topology



Conclusions

We can build spin systems at the nano-scale to generate completely different exotic behaviors, explore topological states both in and out of equilibrium, with unprecedented real-time real-space experimental validation, to test statistical mechanics at the constituent level and to create magnets that do not exist in nature.

Materials and Condensed Matter Physics

People

PhD study

Jobs

Research areas

Colloquia

Current Research Funding

Publications

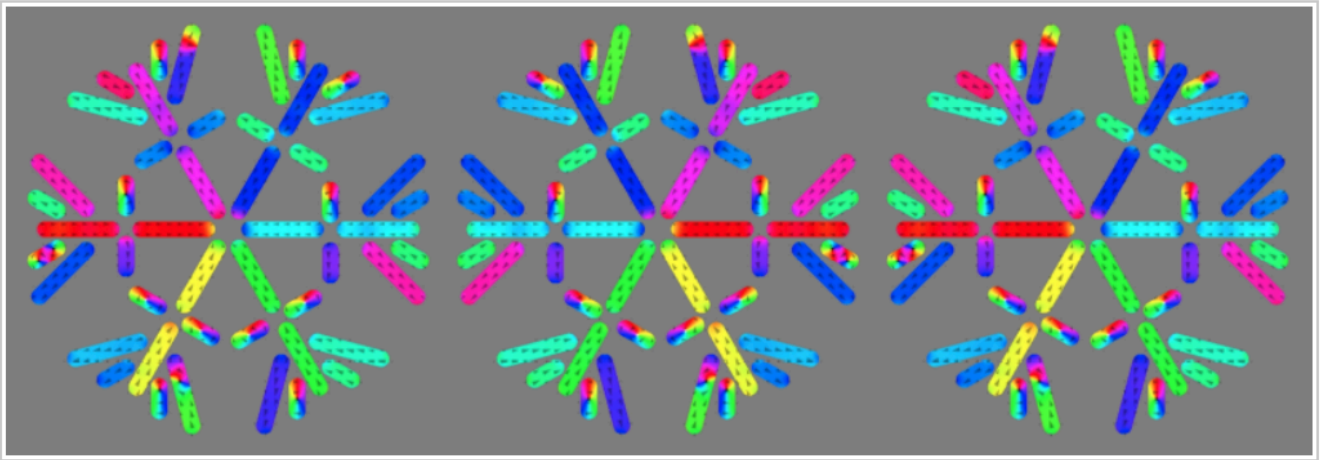
Facilities

Internal Information

Kelvin Nanocharacterisation Centre

Xenon Plasma FIB inauguration

Loch Lomond Workshop on Artificial Spin Ice



The workshop will provide updates on recent experimental and theoretical advances in all aspects of artificial spin ice research including thermally active imaging, frustration by design, and high frequency dynamics.

Dates: 26 to 28 June, 2017

Venue: Lodge on Loch Lomond